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# A USER'S GUIDE FOR THE CONTINUOUS WAVE LASER DAMAGE COMPUTER PROGRAM

R. W. Newman

Johns Hopkins University

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A Continuous Wave Laser Damage computer program (CLAD) has been developed to compute material damage caused by a high power laser beam impinging on material surfaces. The program includes three-dimensional conduction, temperature dependent thermal propertie radiation relief, aerodynamic heating, laser radiation heating, heats of fusion and vaporiz , chemical ablation, and material removal for flat and cylindrical bodies. The program uses finite difference techniques to compute mass loss and temperature histories of laser irradiated metals, ceramics, and ablatives. This report describes the computational methods contained in CLAD, along with some of the assumptions and limitations contained therein. The report is written as a user's manual and contains a description of the main program required to perform a CLAD analysis. Also included is a sample problem, the corresponding main program, and printed output, which will familiarize the user with an actual application of CLAD.



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*Technical Memorandum*

# A USER'S GUIDE FOR THE CONTINUOUS WAVE LASER DAMAGE COMPUTER PROGRAM

by R. W. NEWMAN

THE JOHNS HOPKINS UNIVERSITY • APPLIED PHYSICS LABORATORY
8621 Georgia Avenue ◦ Silver Spring, Maryland ◦ 20910
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# 1. INTRODUCTION AND SUMMARY

Recent progress in the development of high power lasers has evolved lasers capable of causing thermal damage to material surfaces. In order to adequately evaluate the effects of material properties and laser beam characteristics on material damage, a reliable analytical model is needed. After reviewing many of the available analytical models, it was found that most were limited to one-dimensional heat conduction, constant thermal properties, constant irradiation, and no radiation relief or aerodynamic cooling. In many flight applications these effects are significant. Therefore, extensive modifications have been made to the APL finite difference heat transfer program (Ref. 1) to analyze laser heating of flight vehicles. This new program is known as the Continuous Wave Laser Damage Computer Program (CLAD). It computes mass loss and temperature histories of laser heated bodies accounting for three-dimensional conduction, temperature dependent thermal properties, vaporization, melting, chemical reactions, aerodynamic heating, radiation relief, and material removal.

The APL/BBE Continuous Wave Laser Damage Computer Program (CLAD) uses finite difference techniques to predict temperature histories in laser heated materials. The program is written in PL/I computer language, and includes: (a) three-dimensional conduction, (b) thermal properties as functions of temperature (thermal conductivity, thermal capacitance, absorptivity, and emissivity), (c) radiation relief, (d) latent heat of fusion, and (e) laser irradiation of each surface element specified as a function

---

Ref. 1. D. W. Fox, H. Shaw, and J. Jellinek, "Numerical Approximations in Heat Transfer Problems and Usage of IBM 7090 Computer for Solutions," APL/JHU CF-2954, 17 May 1962.



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of time, with an option to specify irradiation by a moving Gaussian beam. CLAD has recently been expanded to include: (a) aerodynamic heating and cooling, (b) material vaporization, (c) chemical reactions at the surface, (d) material removal of vaporized and ablated elements, and (e) cylindrical elements.

This report has been written as a user's manual for the CLAD program and includes an overview of the program, a discussion of assumptions and limitations, a main program description and a sample problem.

## 2. OVERVIEW OF CLAD CALCULATIONS

The following discussion presents a brief overview of calculations performed in CLAD, and is followed by detailed discussions of: (a) the surface energy balance, (b) time step calculations, (c) corrections for blowing, (d) an option for mechanical erosion, and (e) assumptions and limitations.

The CLAD computer program is a finite difference program written for analysis of laser heated plates and cylinders. The program includes radiative and convective heating with heat relief via radiation and conduction. In addition, the program can account for in-depth melting and material removal at the heated surface. The material removal process can be via vaporization or chemical reactions at the surface. The vaporization process occurs at a specific temperature and heat of vaporization, while the chemical reactions occur over a range of surface temperatures and either absorb or release heat at a rate dependent on the surface temperature and the chemical nature of the ablating material.

A pictorial view of some of the parameters included in CLAD is presented in Fig. 1. The program computes a surface temperature ($T_w$) of each zero volume surface node, by iteratively solving an energy balance at the surface. For ablating surfaces the surface energy balance includes a chemical heating term which is obtained from the Equilibrium Surface Thermochemistry Program (EST) (Ref. 2), as a function of surface temperature and local pressure. Following computation of the surface temperature, CLAD computes the ablation mass loss rate as a function of the surface temperature and local pressure. Capacitances of all finite volume elements (2 and 3) are then computed as functions of temperature, and conduction heating rates are computed

Ref. 2. "User's Manual, Aerotherm Equilibrium Surface Thermochemistry Program," Version 3, Aerotherm Corporation, Mountain View, California, Report UM-70-13, May 1970.

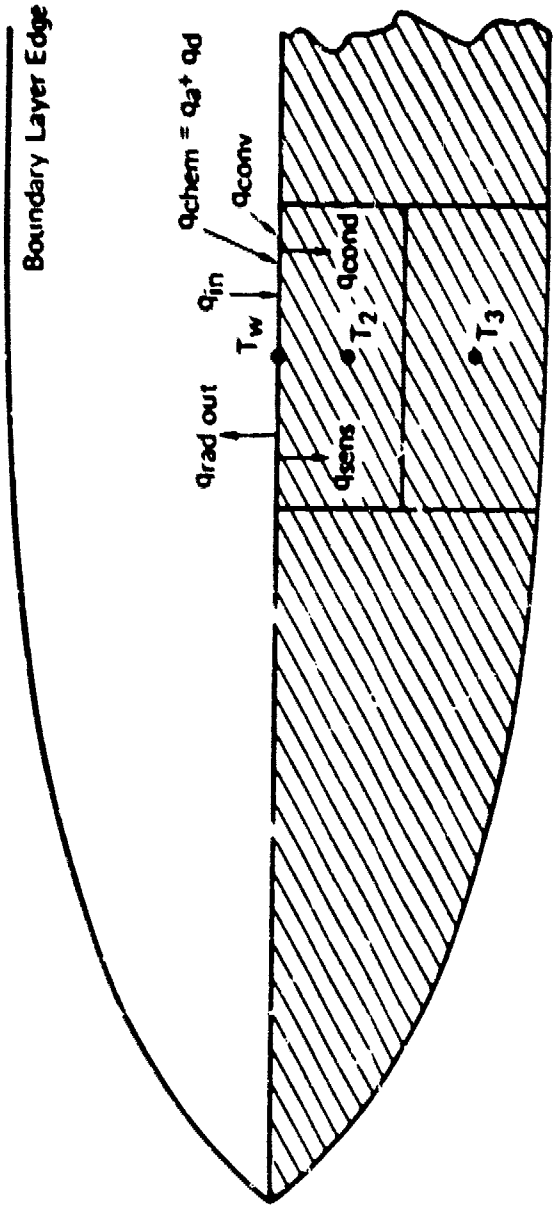


Fig. 1 CLAD Surface Energy Model

between adjacent nodes. A critical stability time step is then used to compute node temperatures at the next time step. Corresponding surface temperatures are then computed for the zero volume surface elements, and the above calculations are repeated for the next time step. This sequence continues until the end time is reached.

## SURFACE ENERGY BALANCE

The chemical reaction model used in CLAD is the same as used in Ref. 3. In this model (Fig. 1) the surface energy balance per unit area is:

$$q_{in} + q_{chem} + q_{conv} + q_{cond} - q_{rad\ out} - q_{sens} = 0. \quad (1)$$

Looking at the individual terms, the incoming heat rate ($q_{in}$) is made up of laser heating and radiative heating as follows:

$$q_{in} = \left[ (q_{las})\ (VIEW) + q_{rad\ in} \right] ALPHA_w , \quad (2)$$

where:

| | |
|---|---|
| $q_{las}$ | is the incident laser heat flux per unit area, |
| VIEW | is a view factor to account for angular beam impingement, |
| $q_{rad\ in}$ | is an incident radiation heat flux per unit area, and |
| $ALPHA_w$ | is the surface absorptivity evaluated at $T_w$. |

---

Ref. 3. "User's Manual Aerotherm Charring Material Thermal Response and Ablation Program," Version 3, Aerotherm Corporation, Mountain View, California, Report RM-70-14, April 1970.

Like all such models, the model used to obtain $q_{chem}$ is an approximation. A discussion of its validity is beyond the scope of this report but has been made in Refs. 4 and 5. In this model (Fig. 1) free stream gases diffuse through the boundary layer to the surface, where they react with the ablating material and either release or absorb heat. The resulting gases are then removed from the surface via diffusion and convective mass transfer into the boundary layer. Appendix A presents a derivation of the chemical heating rate ($q_{chem}$) in terms of diffusion and mass transfer rates.

However, the chemical reaction model contains several important assumptions, which are:

1. All chemical reactions take place at the wall and no reactions occur in the boundary layer.

2. No solid reactants are produced at the wall and no ablative material leaves the surface due to mechanical erosion. For special cases where ATJ graphite is used, mechanical erosion can be included (see Mechanical Erosion Option later in this Section).

3. There is no pyrolysis within the ablative material; all pyrolysis is confined to the surface.

---

Ref. 4. C. B. Moyer and R. A. Rindall, "Finite Difference Solution for the In-Depth Response of Charring Materials Considering Surface Chemical and Energy Balances," Aerotherm Corporation Final Report 66-7, Part II, 14 March 1967 (also NASA CR-1061, June 1968).

Ref. 5. E. P. Bartlett and R. D. Grose, "An Evaluation of a Transfer Coefficient Approach for Diffusion Coefficients," Aerotherm Corporation, Mountain View, California, Report 69-50, 30 June 1969.

4. Gases diffuse through the boundary layer according to their mass concentrating gradients and these gradients are assumed linear through the boundary layer.

5. There is no thermal diffusion of gases in the boundary layer.

The chemical heating term ($q_{chem}$) of Eq. (1) is made up of two parts. The first term ($q_d$) is the rate of energy release due to diffusing gases reacting at the surface. In this process, each free stream specie i diffuses through the boundary layer to the surface where it reacts with the surface and releases heat. The product specie i then leaves the surface at a total enthalpy ($\Delta H_{i,w}$) different than it had on arrival. This heating rate is expressed as:

$$q_d = \rho_e U_e (C_m)_b \sum_{i=1}^{N} (Z_{i,e} - Z_{i,w}) \Delta H_{i,w}, \qquad (3)$$

where:

$\rho_e U_e (C_m)_b \sum_{i=1}^{N} (Z_{i,e} - Z_{i,w})$ is the diffusion mass flow rate of specie i arriving at a unit surface area,

$(C_m)_b$ is the mass transfer Stanton number $(m_d/\rho_e U_e \Delta Z)_b$, corrected for blowing as shown later in this Section (Blowing Rate Correction), with $\Delta Z$ = the diffusion driving potential which produces the diffusion mass flow rate ($m_d$) into the surface,

$Z_{i,e}$ and $Z_{i,w}$ are the diffusion driving potentials for the ith specie diffusing through the boundary layer to the

surface ($Z_{i,e}$ is the potential at the boundary layer edge and $Z_{i,w}$ is the potential at the wall), and

$\Delta H_{i,w}$ is the enthalpy change of each diffusing specie due to its reaction with the surface material ($\Delta H_{i,w} = H_{i,w} - \overline{H}_{rg,w}$).

The second part of the $q_{chem}$ term represents the rate of energy released ($q_a$) by the ablating material as it changes from a solid ablative to reacted gases:

$$q_a = \rho_e U_e (C_m)_b \beta (H_{a,w} - \overline{H}_{rg,w}) , \qquad (4)$$

where

$\rho_e U_e (C_m)_b \beta$ is the ablation rate ($m_a$)

$\beta$ is the ablation to diffusion mass flux ratio defined as $\beta = m_a/\rho_e U_e (C_m)_b$,

$H_{a,w}$ is the total enthalpy (above $T_{ref}$) of the solid ablative material evaluated at the wall temperature ($T_w$), and

$\overline{H}_{rg,w}$ is the total enthalpy (above $T_{ref}$) of the gaseous reactants evaluated at $T_w$ ($\overline{H}_{rg,w}$ is the sum of the chemical and sensible enthalpy of the gases and is averaged according to the mass fraction of each gas present at the surface).

Hence, the total chemical heating term is:

$$q_{chem} = q_a + q_d = \rho_e U_e (C_m)_b \left[ \sum_{i=1}^{N} (Z_{i,e} - Z_{i,w}) \Delta H_{i,w} + \beta (H_{a,w} - \overline{H}_{rg,w}) \right] . \qquad (5)$$

In Eq. (1) the convective heat transfer term is:

$$q_{conv} = \rho_e U_e (C_H)_b (H_r - \overline{H}_{e,w}) , \qquad (6)$$

where:

| | |
|---|---|
| $\rho_e U_e (C_H)_b$ | is the enthalpy based heat transfer coefficient corrected for blowing as will be discussed later, |
| $(C_H)_b$ | is the heat transfer Stanton number corrected for blowing, |
| $H_r$ | is the total recovery enthalpy (above $T_{ref}$), and |
| $\overline{H}_{e,w}$ | is the total enthalpy (above $T_{ref}$) of the gases at the boundary layer edge and evaluated at the wall temperature. |

The convective heat flux is more usually written in the form:

$$q_{conv} = \rho_e U_e (C_H)_b (h_r - h_w) , \qquad (7)$$

where:

| | |
|---|---|
| $h_r$ and $h_w$ | are the sensible recovery and wall enthalpies, respectively. |

The derivation of Eq. (6) from Eq. (7) is given in Refs. 4 and 6.

---

Ref. 6. R. M. Kendall, R. A. Rindall, and E. P. Bartlett, "A Multicomponent Boundary Layer Chemically Coupled to an Ablating Surface," AIAA Journal, Vol. 5, No. 6, June 1967, pp. 1063-1071.

For unity Lewis number, $q_{chem}$ and $q_{conv}$ can be combined and simplified. When the Lewis number equals 1, the mass and thermal boundary layers are coincident in space and $Z_{i,e}$ is evaluated at the thermal boundary layer edge. Hence:

$$(C_H)_b = (C_m)_b ,$$

and

$$(C_m)_b \sum_{i=1}^{N} (Z_{i,e} - Z_{i,w}) \Delta H_{i,w} = (C_H)_b \left[ \overline{H}_{e,w} - \overline{H}_{rg,w} \right].$$

For the unity Lewis number:

$$q_{conv} + q_{chem} = \rho_e U_e (C_H)_b \left[ (H_r - \overline{H}_{rg,w}) + \beta (H_{a,w} - \overline{H}_{rg,w}) \right], \quad (8)$$

where the heat transfer coefficient $\rho_e U_e (C_H)$ and recovery enthalpy $H_r$ are time dependent variables input by the user. The heat transfer coefficient is automatically adjusted for blowing as is discussed later in this Section. The quantity $H_{a,w}$ is obtained from a utility program which computes $H_{a,w}$ as a function of wall temperature as follows:

$$H_{a,w} = \int_{T_{ref}}^{T_w} \frac{(\rho c_p)}{\rho} \, dT . \quad (9)$$

The remaining terms in Eq. (8) are obtained from the Equilibrium Surface Thermochemistry Program (EST) (Ref. 2). For unity Lewis number EST supplies $T_w$ and $\overline{H}_{rg,w}$ as tabular functions of local pressure ($P_L$) and the ablation to diffusion ratio ($\beta$). As part of the CLAD program, a utility subroutine accepts EST output directly and converts it to tables of $\overline{H}_{rg,w}$, $\beta (H_{a,w} - \overline{H}_{rg,w})$, and $\beta$ as functions of $P_L$ and T.

For Lewis numbers not equal to 1, $q_{chem}$ and $q_{conv}$ are as presented in Eqs. (5) and (6), and the EST program

supplies $T_w$, $\overline{H}_{rg,w}$, $\overline{H}_{e,w}$, and $\sum_{i=1}^{N} (Z_{i,e} - Z_{i,w}) \Delta H_{i,w}$ as tabular functions of $P_L$ and $\beta$. The utility subroutine accepts this data directly and converts it to tables of $\overline{H}_{rg,w}$, $\overline{H}_{e,w}$, $\sum_{i=1}^{N} (Z_{i,e} - Z_{i,w}) \Delta H_{i,w} + \beta (H_{a,w} - \overline{H}_{rg,w})$, and $\beta$ as functions of $P_L$ and $T_w$.

The remaining terms in Eq. (1) are:

$$q_{cond} = \frac{K_{w-2}}{L_{w-2}} (T_2 - T_w),$$

$$q_{rad\ out} = F \sigma \epsilon_w (T_w^4 - T_{sp}^4), \text{ and}$$

$$q_{sens} = m_a (h_{a,w} - h_{a,2}),$$

where:

| | |
|---|---|
| $K_{w-2}$ | is the material thermal conductivity evaluated at $(T_w + T_2)/2$, |
| $L_{w-2}$ | is the conduction path length from the wall to node 2, |
| $F$ | is a view factor, |
| $\sigma$ | is the Stefan-Boltzman constant, |
| $\epsilon_w$ | is the surface emissivity, and |
| $q_{sens}$ | is the sensible energy required to raise the ablating material from temperature $T_2$ to surface temperature $T_w$. |

In Ref. 3 this is referred to as the "velocity term."

## TIME STEP CALCULATIONS

At the beginning of time step a, Eq. (1) is solved iteratively for surface temperatures at time $\tau_a$. For ablating surfaces the ablation to diffusion ratio ($\beta$) is found from tables as a function of $T_w$ and $P_L$. $\beta$ is then used to find the ablation mass loss rate per unit area from:

$$m_a = \beta \left[ (\rho_e U_e (C_m)_b \right] ,$$

where:

$$\rho_e U_e (C_m)_b = \rho_e U_e (C_H)_b (C_m/C_H) ,$$

and $\rho_e U_e C_H$ is input as a function of time and corrected for blowing as will be shown later. $C_m/C_H$ is also an input value.

For surfaces that are vaporizing instead of chemically ablating, the surface energy balance becomes:

$$q_{in} + q_{conv} + m_a Q_{vap} + q_{cond} - q_{rad\ out} - q_{sens} = 0, \qquad (10)$$

where $Q_{vap}$ is the heat of vaporization per pound of material. By setting the surface temperature equal to the vapor temperature, Eq. (10) is used to compute $m_a$.

Following computation of $m_a$, the CLAD program computes heat conduction between elements and elemental capacitances These values are then used in the Dusinberre stability equation (Ref. 7) to find the stability time step which equals 90% of the smallest value of:

$$\frac{(\rho c_p V)_i}{\sum_j \left(\frac{KA}{L}\right)_{ij}} ,$$

Ref. 7. G. M. Dusinberre, Heat Transfer Calculations by Finite Differences, International Textbook Co., Scranton, 1961.

where i is all elements having a capacitance associated with them, and the sum is taken over all elements j connected to i. The temperature of interior elements 2, 3, etc. are then computed at time $\tau_b$. If any element has gone above its melt temperature, then subroutine QFUSON computes the melt depth in each element. If an element has not completely melted, then it is set to the melt temperature. If the element is resolidifying then QFUSON accounts for the heat of fusion and reduces the melt depth accordingly.

The laser surface heating rate ($Q_{las}$) is next computed at time $\tau_b$. CLAD then uses the mass loss rate computed at $\tau_a$ to determine the volume of element 2 removed during the time interval $\tau_b - \tau_a$. As the volume of element 2 decreases, the stability time step approaches zero. Therefore, after a specified portion of element 2 (usually 50%) has ablated away, the program lumps the remaining portion with element 3. Element 2 then becomes a zero volume surface node and element 1 is removed from the model (as shown at $\tau_c$ in Fig. 2). In this manner elements are removed without seriously reducing the stability time step.

As each element shrinks, conduction paths to adjacent elements are also changed. Conduction paths perpendicular to the surface are adjusted according to the distance between elements, assuming the node always remains in the center of each element. It is important to remember, that during mass removal, the location of element 2 is continually moving toward the backface.

Thermal resistance between longitudinally adjacent elements are computed as the sum of the resistances of each element. For example the thermal resistance between elements 2 and 5 in Fig. 2 at $\tau_b$ is:

$$\left(\frac{KA}{L}\right)^{-1}_{2-5} = \left(\frac{K_2 A_2}{0.5\, L_{2-5}}\right)^{-1} + \left(\frac{K_5 A_5}{0.5\, L_{2-5}}\right)^{-1} . \qquad (11)$$

where the conductivities $K_2$ and $K_3$ are evaluated at $T_2$ and $T_5$, respectively. At time $\tau_c$ in Fig. 2 the conduction path

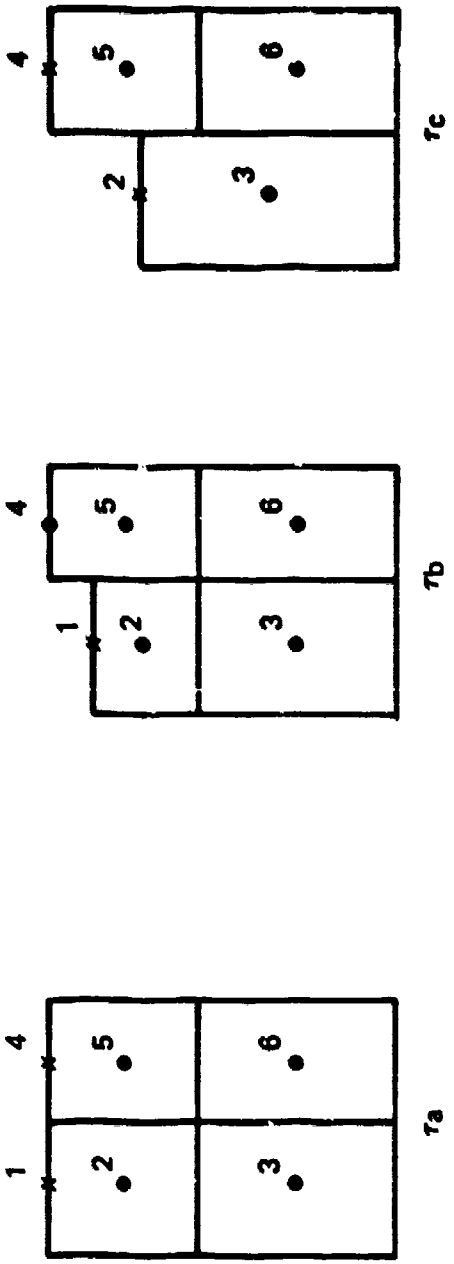


Fig. 2 Schemstic of the Node Dropping Process

between elements 3 and 6 is calculated in the same manner as between 2 and 5 in Eq. (11). Notice that even though elements 3 and 5 have a common interface they are not directly connected; however, they are indirectly connected through element 6.

After computing the thermal resistance between ablating elements the program calculates surface temperatures at time $\tau_b$ using Eq. (1), as done previously at time $\tau_a$. The procedure is continued computing $m_a$, $T_2$, $T_3$, etc. at each time step until the end time is reached.

## BLOWING RATE CORRECTION

The CLAD program automatically reduces the heat and mass transfer Stanton numbers ($C_H$ and $C_m$) to account for the familiar blowing effect according to the equation:

$$(C_H)_b = C_H \frac{\alpha}{e^{\alpha} - 1} \quad , \tag{12}$$

where:

$$\alpha = \frac{2\lambda m_a}{\rho_e U_e C_H} \quad , \tag{13}$$

and $\lambda$ is an empirical constant known as the "blowing parameter." Reference 3 recommends that $\lambda = 0.5$ be used for laminar flow and that $\lambda = 0.4$ correlates with turbulent data somewhat better.

The CLAD program computes $(C_m)_b$ from an analogy bewteen heat and mass transfer, where $(C_m)_b = (C_H)_b \, C_m/C_H$ and the constant ratio $C_m/C_H$ is input to the program.

For graphite, the user has the option of using the Putz and Bartlett correlation (Refs. 8 and 9) instead of Eq. (12). The Putz and Bartlett equations are as follows:

$$(C_H)_b = C_H \left[ 1.0 - 0.6563\,\beta_o + 0.01794\,\beta_o^2 + 0.06365\,\beta_o^3 - 0.01125\,\beta_o^4 \right] , \quad (14)$$

and

$$(C_m)_b = C_H \frac{2\lambda\beta}{e^{2\lambda\beta} - 1} , \quad (15)$$

where:

$$\beta_o = \beta \frac{(C_m)_b}{C_h} , \quad (16)$$

and

$$\lambda = (0.012 + 0.018\,\beta_o + 0.0814\,\beta_o^2) * (0.762 - 0.038\,\beta_o). \quad (17)$$

The user initiates the Putz and Bartlett correlation for graphites by changing CM_CH to a negative value in the CALL ABAROS statement (see Section 3). This also initiates the mechanical erosion option discussed below.

## MECHANICAL EROSION OPTION

In the above discussion of CLAD, the ablation mass loss ($m_a$) is computed assuming no mechanical erosion. At

---

Ref. 8. K. E. Putz and E. P. Bartlett, "Heat Transfer and Ablation-Rate Correlations for Reentry Heat Shield and Nose Tip Applications," AIAA Preprint Paper No. 72-91, January 1974.

Ref. 9. L. L. Perini, "Heat and Mass Transfer Correlation Equations for Subliming Graphite in High Speed Flow," APL/JHU ANSP-M-11, August 1974.

high temperatures and in a high shear environment, mechanical erosion can became significant. Although CLAD, in general, cannot handle mechanical erosion, it does have a special calculation for ATJ graphite, where the total mass loss rate is the sum of the chemical ablation mass loss rate ($m_a$) and the mechanical mass loss rate ($m_{mech}$). In Ref. 10 the $m_{mech}$ is derived from the difference between experimentally measured mass loss data of Lundell and Dickey (Ref. 11) and analytical values computed neglecting mechanical erosion. A curve through the bulk of the points gives:

$$m_{mech} = m_a \left[ \frac{314}{4178 - (T_w/1.8)} - 0.155 \right], \qquad (18)$$

which is applicable over the temperature range $4500 \leq T_w \leq 7245°R$ and local stagnation pressure range $0.3 \leq P_L \leq 4.4$ atm. Since no experimental data are available above 7245°F, $m_{mech}$ is set equal to $1.89\ m_a$ at values above 7245°R. It should be emphasized that the above calculation is only valid for ATJ graphite. The user may initiate the mechanical erosion option by changing CM_CH to a negative number in the CALL ABARO3 statement.

## CLAD – ASSUMPTIONS AND LIMITATIONS

There are several assumptions and limitations in CLAD of which the user should be aware. These are discussed in the following paragraphs:

1. The CLAD program is limited to only one ablating material in any given analysis. This restriction can be eliminated in the future if the need arises, but will require some reprogramming.

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Ref. 10. L. L. Perini, "Review of Graphite Ablation Theory and Experimental Data," APL/JHU ANSP-M-1, December 1971.

Ref. 11. J. H. Lundell and R. R. Dickey, "Graphite Ablation at High Temperatures," AIAA Preprint Paper No. 71-418, April 1971.

Although CLAD is limited to one ablating material there may be several substrates of different materials as long as these substrates don't ablate. In addition CLAD is restricted to models which either chemically ablate or vaporize but cannot handle models which do both. For one-dimensional models, both these restrictions can be handled by running the program twice. The first run was continuous until the first surface layer is completely ablated, then the second run is made using the second surface material initialized to the temperatures at the end of the first run.

The user should realize that although CLAD is restricted to a single ablative per run, it is not restricted to a single vaporizing material per run. It can have several material layers each vaporizing when it becomes the surface layer.

2. As elements ablate or vaporize the surface temperature fluctuates in a "sawtooth" manner caused by node lumping. This sawtoothing is usually not too severe and may be reduced by using smaller elements (Ref. 12).

3. If during a single time step, a vaporizing surface has not yet melted, then its heat of fusion is ignored for that time step. This is usually not very serious since the heat of vaporization is usually much larger than the heat of fusion.

4. As surface elements ablate the node adjacent to the surface is always located in the center of the element. Hence as the element ablates the node is continually moving towards the backface. This

---

Ref. 12. J. D. Randall, "A Survey of Possible Node Dropping Methods for Use in the Standard Heat Transfer Program," APL/JHU ANSP-M-10, August 1974.

can sometimes be confusing when plotting a temperature history of this node, since the element location is not constant.

5. No attempt has been made to heat the side of those elements whose neighboring elements have ablated or vaporized.

6. Mass removal, chemical reactions, and vaporization occur only at the surface.

7. The number of different materials is presently limited to nine. If additional materials are required, CLAD could be reprogrammed to handle them.

Although the CLAD analysis contains several assumptions and limitations, it is still quite general and can be utilized for a wide variety of applications. The programming details necessary for implementing CLAD are discussed in the following section.

# 3. MAIN PROGRAM DESCRIPTION

The CLAD program consists of a series of subroutines called by a main program. A typical main program is as follows:

```
NAME:    PROCEDURE OPTIONS (MAIN)

         DECLARE STATEMENTS

         CALL STORE

         A series of initialization statements
           which might include: GET COPY
           DATA, GET LIST, CALL READRK,
           CALL READTM, CALL READAB,
           and CALL RFOCP3

         CALL THREED*

         CALL SET

11:      IMAX = DECIDE (TIMS, IOX, TIMEI)*

         CALL GAUSBM*

         CALL QFUSON*

         CALL ABARO3

         CALL CAPCN3

         CALL WRITE

         CALL STEP
```

*These statements are optional.



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GO TO I1

END NAME

The order in which the above subroutines are called is very important and should be exactly as shown for the program to function correctly.

A complete description of each section of the main program is presented below. In reading this material, the reader may find it helpful to refer to Appendix B, which presents the main program used to analyze a sample problem discussed later in the text.

1. NAME: PROCEDURE OPTIONS (MAIN) defines procedure NAME as the main program.

2. DECLARE STATEMENTS define all variables and subroutines used in the main program. All subroutines are declared as entry points using DCL ENTRY statements exactly as they appear in the sample problem in Appendix B. In addition all variable names used in the program are declared with the following attributes: FIXED or FLOAT; BINARY or DECIMAL; AUTOMATIC, STATIC, CONTROLLED, or EXTERNAL; and double or single precision. The following variable names must be declared EXTERNAL and must always appear in the declare statements QVAPOR(*), TVAP(*), RO(*), and AIRPRNT. Additional variables declared EXTERNAL for GAUSBM or QFUSON are: IMAX, QMELT(*), TIMS, TMELT(*), and NDX (20, 20). In addition variable names QVAPOR, TVAP, QMELT, TMELT, and RO are specified as CONTROLLED and must be assigned array lengths in an ALLOCATE statement. The array length is equal to the number of vaporizing materials. These variable names are defined as follows:

| | |
|---|---|
| QVAPOR | is an array defining the latent heat of vaporization for each material assigned thermal properties in READRK, where the subscript of QVAPOR is |

| | |
|---|---|
| | the index defining the material (FLOAT BINARY) (Btu/lb), |
| TVAP | is an array of corresponding vapor temperatures (FLOAT BINARY) (°R); TVAP(*) is zero if material I ablates with a chemical reaction instead of vaporizing. (In addition, for cases with vaporization, $\overline{H}_{rg}$ is set to air enthalpy values in the input to READAB. Hence CLAD is restricted to models which either vaporize or chemically ablate, and cannot handle models with both), |
| QMELT | is an array defining the latent heat of fusion for each material assigned thermal properties in READRK, where the subscript of QMELT is the index defining the material (FLOAT BINARY) (Btu/lb), |
| TMELT | is an array of corresponding melt temperatures (FLOAT BINARY) (°R), and |
| RO | is an array of corresponding densities (FLOAT BINARY) ($lb/ft^3$). |

The attributes assigned to other variables in the declare statements are discussed below as they are encountered in the program.

3. CALL STORE (LASCAP, LASCAP, 3) specifies all allocatable variables as arrays of length LASCAP, and

initializes them to 0.0. LASCAP is a fixed binary number equal to the largest capacitor number used in the program. The "3" informs STORE to allocate variables used in routines THREED, QFUSON, ABARO3, and CAPCN3.

4. If variable names are not assigned initial values in the above DECLARE statements, they are given values in one of several ways. One of these is through an assignment statement such as X = 10; Another is through GET statements such as GET LIST (X); or GET COPY DATA. If the variables are a function of temperature then they should be initialized by calling subroutine READRK as follows:

CALL READRK (I, IND, D1, D2, D3, D4, NI, INFILE);

where:

| | |
|---|---|
| I | is an index (FIXED BINARY), |
| IND | the name of the table containing values for the independent temperature variable (FLOAT BINARY array of length NI+1) (°R), |
| D1, D2, D3, D4 | are variable names of tables for the first, second, third, and fourth temperature dependent variables (FLOAT BINARY numbers of length NI), |
| NI | is a number identifying the length of the tables (FIXED BINARY), and |
| INFILE | is the data file from which the tables are to be read (this variable is declared as a |

FILE in the declare statements above. If the input is to be read from data cards then INFILE is SYSIN, (FILE)).

Data cards required for READRK are as follows:

Two comment cards, followed by NI cards, each containing the appropriate values for:

| | |
|---|---|
| IND in columns 1 to 14 | All in F-Format |
| D1 in columns 15 to 29 | |
| D2 in columns 30 to 44 | |
| D3 in columns 45 to 59 | |
| D4 in columns 60 to 75 | |

Thermal properties of each material must be initialized by a call to READRK, where:

| | |
|---|---|
| I | is a unique number from 1 to 9 identifying the material, |
| IND | is temperature ($^{\circ}$R), |
| D1 | is the product of density and specific heat (Btu/ft$^3$.$^{\circ}$R), |
| D2 | is thermal conductivity (Btu/ft$\cdot$h$\cdot^{\circ}$R), |
| D3 | is surface emissivity, and |
| D4 | is surface absorptivity. |

Thermal contact conductances must also be input via READRK, where:

| | |
|---|---|
| I | is a number from 1 to 9 identifying the conductance table (this number must be different from that used for material property tables and other conductance tables), |
| IND | is temperature ($^{\circ}$R), |
| D1 | is a dummy variable or another variable with dependence on temperature, |
| D2 | is contact conductance (Btu/ft$^2 \cdot$h$\cdot^{\circ}$R), |
| D3 and D4 | are dummy or other variables. |

Output from READRK includes the two comment cards and numerical values assigned to each argument.

5. CALL READTM (I, IND, D1, D2, D3, D4, D5, NI, INFILE); reads time dependent variables, where:

| | |
|---|---|
| I | is an index defining the READTM statement (FIXED BINARY), |
| IND | is an array containing values for the independent time variable (FLOAT BINARY array of length NI+1) (seconds), |
| D1, D2, D3, D4, D5 | are arrays of the first, second, third, fourth, and fifth dependent variables (FLOAT BINARY arrays of length NI), |

| | |
|---|---|
| NI | is the length of the above arrays (FIXED BINARY), and |
| INFILE | is the data file from which above arrays are to be read (this variable is declared as a FILE in the declare statements. If input is read from data cards then INFILE is SYSIN (FILE)). |

Data cards required for READTM are as follows:

Two comment cards, followed by NI cards, each containing values for:

| | |
|---|---|
| IND in columns 1 to 9 | All in F-Format |
| D1 in columns 10 to 19 | |
| D2 in columns 20 to 29 | |
| D3 in columns 30 to 39 | |
| D4 in columns 40 to 49 | |
| D5 in columns 50 to 59 | |

6. CALL READAB – Subroutine READAB performs two basic functions. First it computes the enthalpy of the ablative material in its solid state. This is accomplished by trapezoidal integration of the capacitance/density versus temperature curve. The second operation of READAB is to read the thermochemistry data supplied by the EST program (Ref. 2). The subroutine reads this thermochemistry data, changes it to the appropriate units, and adapts it to the form required by subroutine ABARO3. For a Lewis number not equal to 1 the conversion process is as follows. The EST program provides values of gas temperature ($T_{rg,w}$), gas

enthalpy at the surface ($\overline{H}_{rg,w}$), the enthalpy of the gas constitutes at the boundary layer edge evaluated at the wall temperature ($\overline{H}_{e,w}$), and the chemical activity function $\left(\sum_{i=1}^{N} (Z_{i,e} - Z_{i,w}) \Delta H_{i,w}\right)$, all as tabular functions of gas pressure ($P_L$) and the ablation to diffusion mass loss ratio ($\beta$). The EST data is expressed in calories, grams, and °K. READAB has as a parameter the conversion factor required to covert these values to Btu, lbm, and °R. Furthermore, the routine computes $\log_{10} \beta$, $\overline{H}_{rg,w}$, $\overline{H}_{e,w}$, and "QCHEM" as functions of $P_L$ and $T_w$, where:

$$\text{"QCHEM"} = \sum_{i=1}^{N} (Z_{i,e} - Z_{i,w}) \Delta H_{i,w} + \beta (H_{a,w} - \overline{H}_{rg,w}) .$$

Notice that $q_{chem} = \rho u (C_m)_b$ "QCHEM". The values of $T_w$ used in this table are specified in the parameters of READAB.

For a Lewis number equal to 1, READAB converts EST values as follows. The EST program provides values of $T_w$ and $\overline{H}_{rg,w}$ as functions of $P_L$ and $\beta$. The data is converted to units of Btu, lbm, and °R. In addition READAB also computes $\log_{10} \beta$, $\overline{H}_{rg,w}$, and "QCHEM" as functions of $P_L$ and $T_w$, where values of $T_w$ are specified by parameters READAB and "QCHEM" = $\beta (H_{a,w} - \overline{H}_{rg,w})$. Notice that in this case "QCHEM" is a misnomer since it is really a portion of $q_{conv}$ and $q_{chem}$ (Eq. (8)), and cannot be related to $q_{chem}$ alone.

In its output READAB prints the ablative material enthalpy ($H_{a,w}$) Eq. (9), as a function of temperature ($T_w$). It also prints both the dimensionally converted input data from EST as functions of $P_L$ and $\beta$, and the reformated data as functions of $P_L$ and $T_w$. Occasionally one may not wish to have these tables printed in the output as they can be quite lengthy. If so, the following statement is placed in the main program:

```
DCL AIRPRNT INIT(0) FIXED BIN EXT;
```

Subroutine READAB is invoked by the calling sequence:

CALL READAB (#PL, #BETA, LEW#,
RHO, RHOCP, TEMP TWMIN, TWMAX,
TWINC, CONV, INFILE);

where:

| | |
|---|---|
| #PL | specifies the number of pressure entries being supplied by the EST program (FIXED BIN), |
| #BETA | specifies the number of ablation to diffusion mass loss ratio ($\beta$) values being supplied by the EST program at each value of pressure (FIXED BINARY), |
| LEW# | is the Lewis number (FLOAT BINARY), |
| RHO | is the surface material density (FLOAT BINARY) ($lbm/ft^3$), |
| RHOCP, TEMP | is a list of density times specific heat values for the surface material (from which values of $H_{a,w}$ are calculated) (the values correspond to temperatures in the list TEMP (FLOAT BINARY) ($Btu/ft^3$, °R); the length of array TEMP is one greater than array RHOCP), |
| TWMIN, TWMAX, and TWINC | are constants that specify the beginning value of temperature, the ending value of temperature, and the increment of temperature between these limits for the variable |

| | |
|---|---|
| | $T_w$, which is used in converting EST data from fun tion of $P_L$ and $\beta$ to functions of $P_L$ and $T_w$. |
| CONV | is the conversion factor required to convert input data to °R. If data is in °K and cal/g, then CONV = 1.8; otherwise CONV = 1.0 and input data have units of °R and Btu/lbm (FLOAT BINARY), and |
| INFILE | is the data file from which input to READAB is to be read (if input is read from data cards then INFILE is SYSIN (FILE). |

READAB automatically assumes an enthalpy reference temperature ($T_{ref}$) of 536° R. If a different value is desired the user may declare TREF as FLOAT BIN EXT in the main program and assign it the appropriate value in °R.

In addition to the above arguments READAB also receives information from data cards or a data tape. These data consist of: two commentary cards followed by chemical data tables obtained from the EST program. The data are formatted as follows: First there are #BETA cards defining chemical data at a given local pressure ($P_L$) as a function of $\beta$. This set of cards is followed by subsequent sets defining chemical data at other local pressure levels. Hence for each local pressure there are #BETA cards and there are #PL pressures, i.e., #PL*#BETA data cards in the table. #BETA and #PL must be greater than 1.

The data included on each card depend on the Lewis number. If LEW# = 1 then each card contains the following, in F-format:

| | Column | Units |
|---|---|---|
| $P_L$ | 1 to 13 | atmospheres |
| $\beta$ | 14 to 26 | none |
| $T_w$ | 27 to 39 | °C or °R |
| $\overline{H}_{rg,w}$ | 40 to 52 | cal/gm or Btu/lbm |

For nonunity Lewis numbers each card contains the following, in F-format:

| | Column | Units |
|---|---|---|
| $P_L$ | 1 to 13 | atmospheres |
| $\beta$ | 14 to 26 | none |
| $T_w$ | 27 to 39 | °C or °R |
| $\overline{H}_{rg,w}$ | 40 to 52 | cal/g or Btu/lbm |
| $\overline{H}_{e,w}$ | 53 to 65 | cal/g or Btu/lbm |
| $\sum_{i=1}^{N} (Z_{i,e} - Z_{i,w}) \Delta H_{i,w}$ | 66 to 78 | cal/g or Btu/lbm |

It is noted here that the above described variables should not be of direct concern to the user. They do not enter into the calling sequence of any of the subroutines and their allocation and subsequent use of controlled internally by READAB and ABARO3. Their description is included only for completeness.

Both subroutines (ABARO3 and READAB) make use of a number EXTERNAL variables that have not yet been described. These variables are essentially the storage locations for the thermochemical data (supplied by the EST program) as needed by ABARO3 to perform the ablation analysis. These variables are:

**PL** is a one-dimensional array (or list) of pressure values ($P_L$) given by the EST program in atmospheres, and is one of the independent variables for the property data (during actual use, this variable is converted to the base 10 logarithm of the pressure value),

**BETA** is a list of ablation to diffusion mass loss ratio values ($\theta$) supplied by the EST program and is the other independent variable for the given property values (during actual use this variable contains the natural logarithm of $\beta$),

**TW** is a two-dimensional array of values specifying absolute temperature ($^\circ$R) (each row of this dependent variable is a list of values for which the pressure is constant and given by the corresponding value in PL),

**TWI** is a one-dimensional array of temperatures ($^\circ$R) specified by TWMIN, TWMAX, and TWINC as described above (this list is the independent variable used with PL to describe QCHEM, HW, and HEW,

**QCHEM** is a two-dimensional array of either

$$\left[\sum_{i=1}^{N} (Z_{i,e} - Z_{i,w})\,\Delta H_{i,w}\right] + \beta\,(H_{a,w} - \overline{H}_{rg,w})$$

for a Lewis number not equal to 1, or

$$\beta\,(H_{a,w} - \overline{H}_{rg,w})$$

for a Lewis number equal to 1, converted by READAB to depend on PL and TWI (Btu/lb),

HW — is a two-dimensional array of wall enthalpy ($\overline{H}_{rg,w}$) converted by READAB to depend on PL and TWI (Btu/lb), and

HEW — is a table of enthalpy of gases at the boundary layer edge ($\overline{H}_{e,w}$) evaluated at $T_w$, converted to depend on PL and TWI by READAB (Btu/lb).

To summarize the function of READAB with respect to the thermochemical data, the following sequence is listed;

1. The EST program is run to produce output of $\overline{H}_{rg,w}$, $T_w$, $\overline{H}_{e,w}$ and the chemical activity function:

$$\sum_{i=1}^{N} (Z_{i,e} - Z_{i,w}) \Delta H_{i,w}$$

as bivariant tables depending on local pressure $P_L$ and ablation to diffusion mass loss ratio $\beta$.

2. The above EST output is rearranged so that the pressure and $\beta$ values are ascending in magnitude and are then reformatted for input to READAB according to the following format:

| | Format | Columns |
|---|---|---|
| $P_L$ | F-format | 1 to 13 |
| $\beta$ | F-format | 14 to 26 |
| $T_w$ | F-format | 27 to 39 |
| $\overline{H}_{rg,w}$ | F-format | 40 to 52 |

| | Format | Columns |
|---|---|---|
| $\overline{H}_{e,w}$ | F-format | 53 to 65 |
| $\sum_{i=1}^{N} (Z_{i,e} - Z_{i,w}) \Delta H_{i,w}$ | F-format | 66 to 78 |

(There is available a simple reformatting utility program which accepts EST format and produces punched output in the above described APL format. Note that for a Lewis number equal to 1 the last two items may be omitted.)

3. The reformatted EST output is placed in the input stream of the CLAD job and is read by subroutine READAB.

4. READAB applies the conversion factor CONV and prints out the converted input. This printed output will contain, in addition to the data supplied, the calculated values of "QCHEM".

5. The variables $\overline{H}_{rg,w}$ and "QCHEM" are then converted to depend on $P_L$ and $T_w$. The results of this conversion are then printed out.

6. Subroutine ABARO3 uses the converted data, stored in the appropriate EXTERNAL variables by READAB, to solve the required surface energy balances.

Since the thermochemical data are supplied as tables, extensive use of interpolation is required to obtain the precise values needed in ABARO3. This interpolation, while not of direct concern to the user, is done in a logarithmic sense with regard to pressure ($P_L$) and ($\theta$). When these variables are required for use in interpolation, their logarithms are first taken and then the linear interpolation is performed. The antilog of this interpolated result is then supplied as the required value. This completed the discussion of READAB.

7. CALL THREED and CALL REDCP3 – Geometric data necessary to describe each capacitor in the thermal network are input to the CLAD program in one of two ways. For evenly spaced, rectangular elements the user can call subroutine THREED to automatically divide the model into elements and made the appropriate thermal connections. For nonrectangular elements and for unevenly spaced rectangular elements the user can use subroutine REDCP3 to read the geometry data. These two subroutines are used as follows:

a. CALL THREED – Subroutine THREED divides the analytical model into rectangular elements similar to Fig. 3a. The body is divided into finite volume subsurface elements and zero volume elements on the irradiated surface. All nodes are located at the center of each element. The length of the test section is specified for the x, y, and z directions with each length divided into a specified number of elements. In the z direction the model may be made up of several different materials separated by contact conductances. Each material and contact conductance is assigned an identification number corresponding to the number (I) in READRK. The largest permissible identification number is 9. However, each material and contact conductance may be used more than once, which permits an unlimited number of layers in the Z direction.

THREED also contains an option which allows for a slightly different element break-up as shown in Fig. 3b. In this configuration elements adjacent to the xz and yz planes are half as large as the interior elements and have their nodes located on the planes. This configuration may be particularly useful when analyzing stationary laser beams or other arrangements having two planes of symmetry. In both models elements are numbered sequentially starting at $x = 0$, $y = 0$, $z = 0$ and going first in the z direction, then x, then y (as shown in Fig. 3b). In addition to dividing the model into elements, THREED also computes the volume of each element and the area to length ratio between adjacent elements. These values are stored in the array, XCAP, and passed on to subroutine CAPCN3 (see Number 13 following).

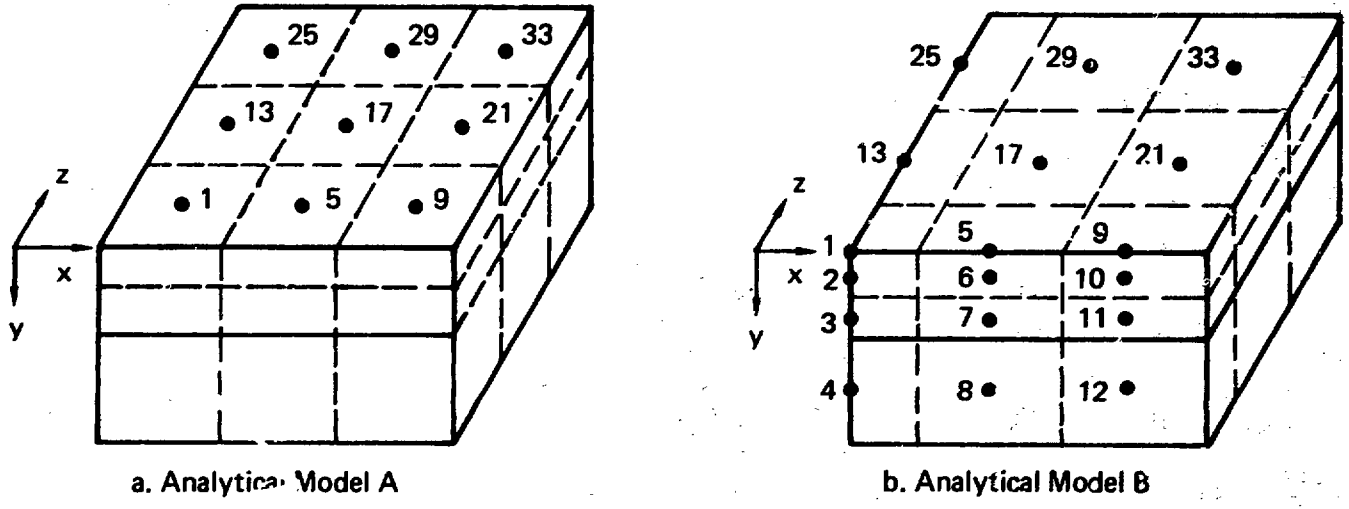


**Fig. 3 Two Models Used in Subroutine THREED to Subdivide Rectangular Bodies into Elements**

CALL THREED (J, LX, NX, LY, NY, NMZ, LZ, NZ, IPROP, ICONT, FEL, SURF);

where:

| | |
|---|---|
| J | is an index identifying the THREED statement (FIXED BINARY), |
| LX, NX, LY, NY | is the model length and number of nodes in the x and y directions (lengths LX and LY are float binary numbers in feet, while NX and NY are fixed decimal values not greater than 10), |
| NMZ | is the number of material layers in the z direction (a fixed decimal number from 1 to ∞), |
| LZ | is an array defining the length of each material layer in the z direction starting with the irradiated material (LZ is a float binary array of size NMZ with units of feet), |
| NZ | is an array of length NMZ defining the number of elements in each material layer (FIXED DECIMAL), |
| IPROP | is an array of length NMZ identifying the material property tables for each layer (FIXED DECIMAL), where IPROP(1) is the property index of the material at the irradiated surface and IPROP(2) is the property index of the adjacent material, and so forth (values assigned |

to IPROP must correspond to the appropriate I in READRK),

ICONT — is an array of length (NMZ-1) identifying tables defining contact conductivity between material layers, starting with ICONT(1) for the conductance between the irradiated material (IPROP(1)) and the adjacent layer (IPROP(2)) (FIXED DECIMAL),

FEL — is the index number of the element located at (0, 0, 0) in Fig. 3 (FIXED DECIMAL), and

SURF — is a flag (if SURF = 0.0 the model is as shown in Fig. 3a; however, if SURF = 1.0 then the model is as shown in Fig. 3b (FLOAT BINARY).

The output from THREED is in a tabular format with the following headings:

I1 VOLUME MATERIAL #CON I2 A/L I3 or A A/L I4 A/L I5 A/L

These headings are followed by a table of corresponding values. The headings stand for:

I1 — is the element in question,

VOLUME — is the volume of element I1 ($ft^3$),

MATERIAL — is a single digit number identifying the material of element I1 (if I1 has a contact conductance connecting it to I2 then MATERIAL is a three digit number, the first digit

| | |
|---|---|
| | identifying material (I1), the second digit identifying the contact conductivity, and the third digit identifying material (I2)), |
| #CON | specifies the number of conduction paths from I1 to elements with identifiers greater than I1, |
| I2 | is the element to which I1 conducts, |
| A/L | is the area to length ratio of element I2 (feet) (if there is a contact resistance between I1 and I2 then A/L is the the area to length ratio between I1 and the contact interface (feet), |
| I3 or A | if I1 and I2 have a contact resistance between them, then I3 is the area of contact interface ($ft^2$), otherwise I3 is the second element to which I1 conducts, |
| A/L | if I1 and I2 have a contact resistance between them then A/L is the area to length ratio between the interface and I2 (feet), otherwise A/L is the area to length ratio between elements I1 and I3 (feet), |
| I4 | is the element to which I1 conducts, |
| A/L | is the area to length ratio between I1 and I4 (feet), |
| I5 | is the element to which I1 conducts, and |
| A/L | is the area to length ratio between I1 and I5 (feet). |

The reader should note that, by convention, the element located below I1 must be I2. However if there is no element below I1 then I2 is a side element. Also note that the printout contains only connections to elements located below, to the right, and behind element I1.

b. CALL REDCP3 (INFILE) — Subroutine REDCP3 reads the geometric data necessary to describe each capacitor in the thermal network. The only argument to REDCP3 is INFILE which is the name of the file containing the data. The data list consists of: two comment cards followed by two data cards for each capacitor in the network to be described. The data defining each capacitor is the same as discussed in the printout of subroutine THREED.

The necessary card format and units are listed below:

| Data | Column | Format | Units | |
|---|---|---|---|---|
| Capacitor number (I1) | 0 to 4 | Fixed | | |
| Volume | 5 to 19 | E-format | $ft^3$ | First data card |
| Material | 20 to 29 | F-format | | |
| #CON | 30 to 39 | F-format | | |
| I2 | 40 to 49 | F-format | | |
| A/L | 50 to 59 | E-format | feet | |
| I3 | 60 to 69 | F format | | |
| A/L | 70 to 79 | E-format | feet | |
| I4 | 0 to 9 | F-format | | |
| A/L | 10 to 19 | E-format | feet | Second data card |
| I5 | 20 to 29 | F-format | | |
| A/L | 30 to 39 | E-format | feet | |

By convention, I2 is always the element adjacent to I1 in the direction of ablation (if there is such an element). In addition, elements in an ablating string must be numbered consecutively starting with the element at the ablating surface.

8. CALL SET (START, STOP, TEMPIN, L, INDEX, TEMP); – Subroutine SET specifies the start and end times of the computer analysis and sets all elements to their initial temperature. The arguments of SET are:

| | |
|---|---|
| START, STOP | start computation at time START and stop at STOP (FLOAT BINARY) (seconds), |
| TEMPIN | all elements are initialized to temperature TEMPIN (FLOAT BINARY) ($^\circ$R), |
| L | the number of elements to be initialized to temperatures other than TEMPIN (FIXED BINARY), and |
| INDEX, TEMP | arrays of length L defining the index and temperature of elements not initialized to TEMPIN (FIXED BINARY and FLOAT BINARY), where TEMP has units of $^\circ$R. |

9. I1: IMAX = DECIDE (TIMS, IOX, TIMEI); – This statement defines the maximum intensity (IMAX) of the Gaussian beam at a specific time, TIMS:

| | |
|---|---|
| IMAX | is the maximum beam intensity at time, TIMS (FLOAT BINARY EXTERNAL) (Btu/ft$^2$ · s), |
| TIMS | is the present time (FLOAT BINARY EXTERNAL) (seconds), |

| | |
|---|---|
| IOX | is an array of maximum intensity as a function of time (FLOAT BINARY) (Btu/ft$^2$ · s), and |
| TIMEI | is the corresponding time where: TIMEI(1) is the number of entries in the table, TIMEI(2) is the time corresponding to IOX(1), etc. (FLOAT BINARY) (seconds). |

If the surface is not irradiated by a Gaussian beam then the above statement may be replaced by a series of statements defining the heating rate to each surface node as a function of time. For example:

I1: Q(J) = DECIDE (TIMS, QJ, TIMEJ);

where:

| | |
|---|---|
| Q(J) | is the heating rate to element J (FLOAT BINARY EXTERNAL CONTROLLED) (Btu/h), |
| TIMS | is the present time (FLOAT BINARY EXTERNAL) (seconds), |
| QJ | is an array defining heating rate to element J as a function of time (FLOAT BINARY) (Btu/h), and |
| TIMEJ | is the corresponding time (FLOAT BINARY) (seconds) where TIMEJ(1) = length of table and the remaining values define times for values given in QJ. |

10. CALL GAUSBM (XO, TIMEG, XINIT, RBEAM, XN, TIMEP); – GAUSBM is called if the surface is being irradiated by a Gaussian beam. The beam may be stationary

or may move along the x axis as a function of time. In either case the beam center is assumed to be on the x axis. Within GAUSBM the heating rate to each surface element is computed from the equation:

$$Q(J) = IMAX * AREA * \exp(-XN * XY^2/RBEAM^2) , \quad (19)$$

where JMAX is the maximum beam intensity at time (TIMS), AREA is the surface area of element J, XY is the distance from the beam center to the element J, XN is a constant, and RBEAM is the beam radius.

The arguments to GAUSBM are:

| | |
|---|---|
| XO | is an array defining the distance from x = 0 to the beam center measured along the x axis as a function of time (FLOAT BINARY) (feet), |
| TIMEG | is the corresponding array of time (FLOAT BINARY) (seconds) TIMEG(1) = length of array XO, |
| XINIT | is the initial location of the beam center along the x axis measured from x = 0 (FLOAT BINARY) (feet), |
| RBEAM | is the radius at which the intensity is $\exp^{-XN}$ * IMAX (FLOAT BINARY) (feet), |
| XN | is the constant in Eq. (19) (usually either 1.0 or 2.0) (FLOAT BINARY), and |
| TIMEP | is an array listing desired printout times of surface intensity, usually the same as specified in WRITE (FLOAT BINARY) (seconds). |

At times specified by TIMEP subroutine GAUSBM prints the following:

BEAM DEFINITION

CENTERED AT X = ____ FT  IMAX = ____ BTU/S FT ** 2

IRRADIATED ELEMENT AREA = ____ FT ** 2

INTENSITY AT EACH ELEMENT (BTU/S * FT ** 2)

I (___) = ____ I (___) = ____ I (___) = ____, etc., etc.

If the elements are not divided such that each element has the same surface area, then the IRRADIATED ELEMENT AREA given above is the area of elements not adjacent to either the x or y axes.

11. CALL QFUSON; – QFUSON computes the latent heat of fusion remaining as an element is heated or cooled at its melting point. Values of latent heat of fusion (QMELT), melt temperature (TMELT) and density (RO) for each material are obtained from the main program as EXTERNAL variables.

12. CALL ABARO3 (I, #SURF, CYL, LAMBDA, TSP, CM_CH, LEW#, VIEW, FACTOR, TLIM, QLIM, ITLIM, TIMEP, IPLOT); – ABARO3 computes the temperature of each zero volume surface node using the energy balance given in Eq. (1). The equation is solved iteratively using temperature dependent values of surface absorptivity, material thermal conductivity, emissivity, and chemical energy. ABARO3 also removes material from ablating and vaporizing elements, and adjusts conduction paths to adjacent elements.

Arguments of ABARO3 are:

I  is an index identifying the ABARO3 statement (FIXED BINARY),

| | |
|---|---|
| #SURF | is the number of surface elements being aerodynamically heated in the call statement (FIXED BINARY), |
| CYL | is a flag for cylindrical or rectangular geometry (FIXED BINARY), |
| | Input: 0 for rectangular elements<br>1 for heating on the outer surface of cylindrical elements<br>-1 for heating on the inner surface of cylindrical elements, |
| LAMBDA | is the "blowing parameter" in Eq. (13) (FLOAT BINARY) (a complete discussion of LAMBDA is presented in Ref. 3 — the "classical" value is LAMBDA = 0.5; however, Ref. 3 recommends that LAMBDA = 0.5 for laminar flow and LAMBDA = 0.4 for turbulent data), |
| TSP | is the radiation space temperature (FLOAT BINARY) ($^{\circ}$R), |
| CM_CH | is the ratio of mass transfer Stanton number to heat transfer Stanton number (FLOAT BINARY) (if CM_CH is negative then the mechanical erosion is included as presented in Eq. (18), and the Putts and Bartlett blowing equations are used — Eqs. (14) through (17)), |
| LEW# | is the Lewis number (FLOAT BINARY), |
| VIEW | is the view factor of incoming laser irradiation (FLOAT BINARY) (note this value |

applies only to laser irradiation and not to $q_{rad}$; see Eq. (1)),

FACTOR — is a lumping factor (if the volume of chemically ablating or vaporizing element drops below this fraction of its original volume, then it is lumped with the element below (FLOAT BINARY)),

TLIM — is the temperature convergence limit of energy balance Eq. (1) (FLOAT BINARY) ($^{\circ}$F),

QLIM — is the heat convergence limit of energy balance (FLOAT BINARY) (Btu/ft$^2$ · s),

ITLIM — is the maximum number of iterations allowed for convergence of energy balance to within the two tolerance values listed above (FIXED BINARY); if this limit is exceeded then the following message is printed and the program continues:

ITERATION ON SURFACE NODE #____ HAS EXCEEDED ____ TSURF =

____ AND DELTA TSURF = ____. HEAT IMBALANCE = ____. ,

TIMEP — is an array of printout data (FIXED BINARY) (seconds),

IPLOT — is a flag for plotting data (FIXED BINARY) if 0 then plots are not desired (if nonzero then many of the values computed in ABARO3 are stored in the temperature vector and may be plotted by calling subroutine PLOTTER;

for more information on the use of this routine the reader is referred to Ref. 13). The following values are stored in the temperature array T:

T(IPLOT) = $\beta\left(\frac{C_m}{C_H}\right)_b$ ,

T(IPLOT+1) = total mass loss ($lbm/ft^2$),

T(IPLOT+2) = mass loss rate ($lbm/ft^2 \cdot s$),

T(IPLOT 3) = accumulated error in the surface energy balance ($Btu/ft^2$),

T(IPLOT+4) = current error in the surface energy balance ($Btu/ft^2 \cdot s$),

T(IPLOT+5) = current recession rate (in/s),

T(IPLOT+6) = total recession (inches),

T(IPLOT+7) = convective heating rate ($\rho_e U_e (C_H)_b (H_r - \overline{H}_{e,w})$) when the Lewis number does not equal 1; and when the Lewis number equals 1 then T(IPLOT+7) is he first term in Eq. (8), i.e. ($\rho_e U_e (C_H)_b (H_r - \overline{H}_{rg,w})$) ($Btu/ft^2 \cdot s$),

T(IPLOT+8) = accumulated conduction away from the surface ($Btu/ft^2$),

T(IPLOT+9) = current heating rate from the "QCHEM * $m_a$ term ($Btu/ft^2 \cdot s$) where: for a Lewis number not equal to 1,

---

Ref. 13. R. K. Frazer, "A Subroutine for Obtaining CalComp Plots of SHTP Variables," APL/JHU EM-4496, 13 December 1972.

$$\text{"QCHEM"} = \sum_{i=1}^{N} (Z_{i,e} - Z_{i,w})\,\Delta H_{i,w} + \beta\,(H_{a,w} - \overline{H}_{rg,w})$$

and for a Lewis number equal to 1,

$$\text{"QCHEM"} = \beta\,(H_{a,w} - \overline{H}_{rg,w}).$$

T(IPLOT+10) = accumulated heating from the "QCHEM" * $m_a$ term (Btu/ft$^2$),

T(IPLOT+11) = current radiative energy flux absorbed at the surface, including laser radiation and radiation from a radiating body (Btu/ft$^2$ · s),

T(IPLOT+12) = current heat radiating from the surface (Btu/ft$^2$ · s),

T(IPLOT+13) = current conduction loss rate from the surface (Btu/ft$^2$ · s),

T(IPLOT+14) = current rate of sensible energy required to heat the ablating material from the node temperature ($T_2$ in Fig. 1) to the surface temperature ($T_w$) (Btu/ft$^2$ · s),

T(IPLOT+15) = surface node number,

T(IPLOT+16) = current value of surface node area (ft$^2$),

T(IPLOT+17) = current radius of surface node (feet), and

T(IPLOT+18) = accumulated sensible energy required to heat ablating material from $T_2$ to $T_w$ (Btu/ft$^2$).

Since the above information is stored in temperature array (T) it is necessary that IPLOT be greater than the largest element number in the analysis. Also, be sure to set LASCAP to a large enough value in statement 3.

In addition to its arguments, ABARO3 also receives information in the form of data cards. Data input in this manner are the surface area and radius of each surface element aerodynamically heated in this call statement. Therefore, there will be #SURF cards, each containing: the surface element number, the surface area ($ft^2$), and the surface radius (feet). If the elements are not cylindrical a radius of 0.0 may be input. There is no column or format restriction on these input data.

13. CALL CAPCN3; – CAPCN3 computes capacitance of each element and heat conduction between elements using geometry values placed in array XCAP by THREED or REDCP3. No arguments are required for CAPCN3, since all values are obtained from previously computed EXTERNAL variables.

14. CALL WRITE (TIMEP); – Subroutine WRITE prints out element temperatures at times specified in array TIMEP.

| | |
|---|---|
| TIMEP | is an array of desired printout times (FLOAT BINARY) (seconds) (if TIMEP(1) is a negative, nonzero number, the output will be printed for each time step). |

15. CALL STEP (MINSTP, MAXSTP); – Subroutine STEP computes the stability time step and the element temperatures at the next step in time.

| | |
|---|---|
| MINSTP | is the minimum allowable time step (FLOAT BINARY) (seconds), and |
| MAXSTP | is the maximum allowable time step (FLOAT BINARY) (seconds). |

If the time step is greater than MAXSTP then it will be set to MAXSTP and the program continues. However, if the

time step is less than MINSTP, the following message is printed and the program is terminated.

TIME STEP LESS THAN MINIMUM ALLOWED

CRITICAL INDEX NO. _____ DELTIM = _____

If subroutine WRITE has printed during the present time step then STEP prints the following:

CRITICAL INDEX NO. = _____ TIME STEP = _____ SEC.

**********

The row of asterisks signifies the end of printout for the present time step. When the end time has been reached (i.e. time STOP as defined in the argument of SET), the following message is printed and the program is terminated:

THE TIME IS _____ SECONDS, AND THE NUMBER OF

STEPS EXECUTED WAS _____.

16. GO TO I1; – Sends control of the program back to I1, which is the first statement in the time loop (see Step 9). Note that the loop is exited via the routine step and is not infinite.

17. END NAME; – This statement signifies the end of MAIN program NAME.

# 4. SAMPLE PROBLEM

Each phase of the CLAD program has been checked against available analytical and/or experimental data. The main program used to check ablation computations in CLAD is presented here as a sample problem. A schematic of the analytical model is shown in Fig. 4. The model consists of a cylindrical, ATJ-S blast tube, convectively heated on the inner surface. From Ref. 14 the enthalpy based convective heat transfer coefficient is 3.96 $lb/ft^2 \cdot s$ and the recovery temperature is 4880°R. The chemical ablation data for ATJ-S graphite was obtained from the EST computer program (Ref. 3) using a reference temperature of 536°R. Hence, the recovery enthalpy above 536°R is the enthalpy of air at 4880° R minus the enthalpy of air at 536, which is 1416 - 129 or 1287 Btu/lb.

The cylinder is 1.4 inches thick and has an inner radius of 0.435 inch. The analysis begins at 0.2 second with the model temperature distribution shown in Fig. 4.

The main program (ABMAIN) used in the analysis is presented in Appendix B. The reader should refer to Appendix B as the statements of ABMAIN are discussed below. ABMAIN is divided into sections headed by comment cards:

/* DECLARE ENTRY STATEMENTS */

Under this heading are entry points for all subroutines called in ABMAIN.

/* DECLARE VARIABLES */

These statements declare variable names used in call statement arguments. These variables are discussed later, as they are encountered in the CALL statements.

---

Ref. 14. R. K. Frazer, "Preliminary Calculations of Temperature and Ablation Histories for a Proposed Blast Tube at ARC," APL/JHU EM-4547, 7 January 1974.

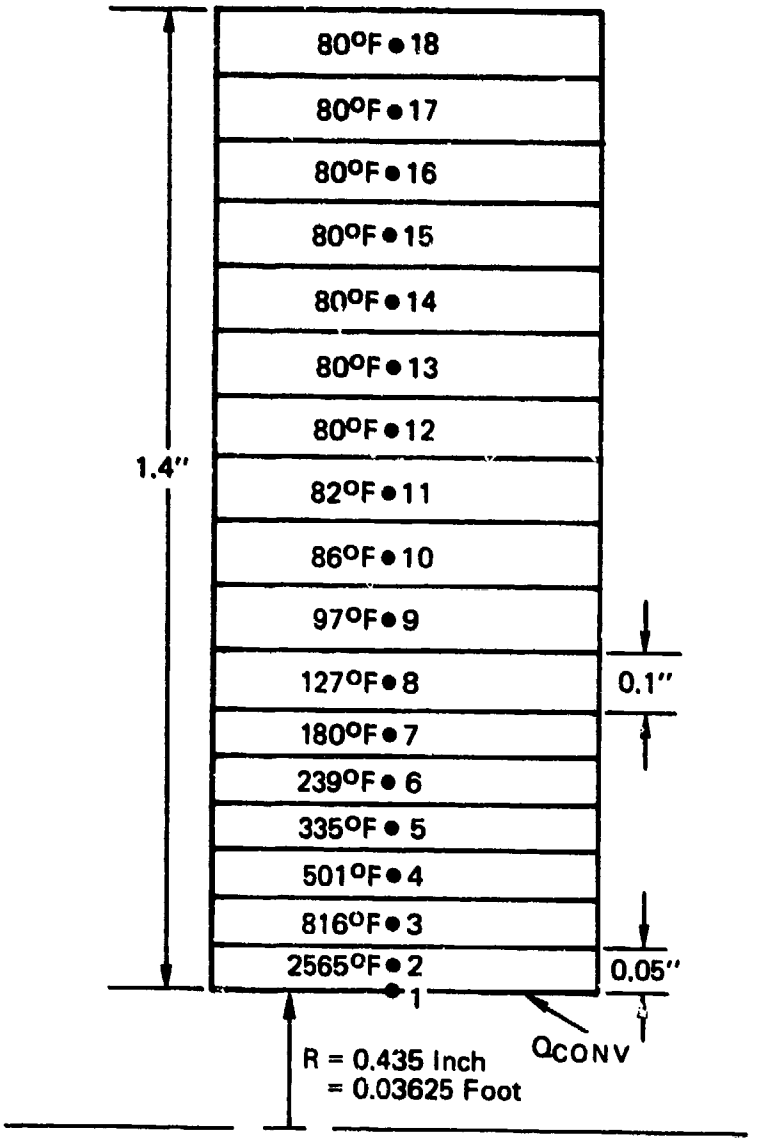


**Fig. 4 Sample Problem — Blast Tube Model**

/* ALLOCATE AND INITIALIZE VARIABLES */

The allocate statement assigns space to controlled variables RO, QVAPOR, and TVAP, while the GET COPY DATA statement assigns initial temperatures to elements 2 through 11. Subroutine STORE assigns an array size of LASCAP to allocatable variables used in the laser heating subroutines. The remaining statements assign printout times to variable TIMEP.

/* READ INPUT DATA */

In this section values are assigned to variables which have not been previously initialized in the above declare statements. The first few statements read and print values for heat of vaporization (QVAPOR), vapor temperature (TVAP), and material density (RO) of the first material. These statements are followed by call statements which read input values.

READRK assigns thermal properties to material 1 as a function of temperature.

READTM assigns time dependent values to recovery enthalpy (HR1), radiation heating rate (QRAD), cold wall enthalpy based heat transfer coefficient (RHOCH1) and local pressure (PLTM1).

Since the Lewis number equals 1, READAB reads local pressure and $\beta$ dependent values of wall temperature ($T_w$) and reacted gas wall enthalpy ($\overline{H}_{rg,w}$). Using these values READAB computes "QCHEM" i.e., $[\beta (H_{a,w} - \overline{H}_{rg,w})]$ and $\overline{H}_{rg,w}$ as functions of $\log_{10}$ (PL) and wall temperature ($T_w$).

REDCP3 reads the volume of each element and the conduction paths between elements.

/* INITIALIZE MODEL TEMPERATURE */

CALL SET specifies the analysis to run from 0.2 (TZERO) to 0.5 (ENDTIME) second. SET also initializes elements 12 through 18 to 540°R (TINIT) and assigns elements 2 through 11 the initial temperatures read in GET COPY DATA.

/* STATEMENTS IN THE TIME STEP LOOP */

Subroutine ABARO3 computes model surface temperatures, ablation rates, heat of vaporization, and chemical heat of reaction, and adjusts conduction paths to ablating elements. The first argument indicates this is the first call to ABARO3. There is one (#SURF) surface node and it is located on the inside of a cylinder (CYL = -1). The blowing parameter constant is 0.4 (LAMBDA) and the surface radiates to a 0.0°R space temperature (TSP). The ratio of mass transfer to heat transfer is 1, as is the Lewis number. If there were laser irradiation, it would impinge on the surface with a view factor of 1 (VIEW). When half (FACTOR) an element is ablated it is then lumped with the adjacent element. Convergence criteria for the surface temperature iteration are ± 0.1°F (TLIM) and ± 0.5 Btu/ft$^2$ (QLIM). The iteration stops after 10 (ITLIM) iterations. Printout times are specified in TIMEP and there are no plots (PLTCODE = 0).

CALL CAPCN3 computes heating rates between elements and has no arguments.

CALL WRITE specifies printout times (TIMEP).

CALL STEP indicates the critical time step is not to be less than 0.005 second (MINSTP) or greater than 0.5 second (MAXSTP).

TO TO IMX: sends control of the program back to the beginning of the time loop.

END ABMAIN: signifies the end of MAIN procedure.

The main program is followed by data cards which are listed in Appendix B in the order they are required in the MAIN procedure. Data cards define the following variables:

1. The number of elements to be assigned initial temperatures and a table of temperatures and corresponding element numbers.

2. Heat of vaporization, vapor temperature, and density of material number 1. Zero vapor temperature indicates the material is ablating and not vaporizing.

3. Temperature dependent values of capacitance, conductivity, emissivity, and absorptivity for material number 1.

4. Time dependent values of recovery enthalpy, input radiation, enthalpy based heat transfer coefficient, and local pressure at the surface.

5. Pressure and $\beta$ dependent values of wall temperature ($T_w$) and gas enthalpy at the wall ($\overline{H}_{rg,w}$) for the ablative material in air.

6. Geometry values defining each element, its volume, its material, the number of elements connected to it via conduction, and the adjacent conduction elements and corresponding area to length ratio.

7. The surface area and radius of element 1.

This ends the sample problem computer program. The reader should realize this program has been written in a general form which allows its application to a great many problems simply by changing a few data cards. This makes parametric studies very easy and eliminates recompilation of the MAIN program for each run.

Printout resulting from the above program is shown in Appendix C. The first six and one half pages consist of input data for the GET COPY DATA, GET LIST, READRK, READTM, READAB, REDCP3, and ABARO3 statements of the MAIN program (see above discussion of input data). This is followed by a series of values computed for each time step. At a typical time step (0.2317 second) the first call to ABARO3 prints the following values: recovery enthalpy = 1287 Btu/lb, cold-wall enthalpy based heat transfer coefficient = 3.960 lb/ft$^2$·s, local pressure = 100 atmospheres, ratio of mass transfer to heat transfer = 1, Lewis number = 1, blowing coefficient = 0.4, and radiation space temperature = 0.0001°R. Node number 1 has a "convective heating rate" of 2925.3 Btu/ft$^2$·s and a cumulative "convective heating rate" of 90.2 Btu/ft$^2$. When the Lewis number is equal to 1, as in this case, the "convective heating rate" is a misnomer and is really equal to the first term in the right side of Eq. (8), i.e., $\rho_e U_e (C_H)_b (H_r - \overline{H}_{rg,w})$. Continuing with the printout in Appendix C, there is no incoming radiation and the mass loss rate is 0.6484 lb/ft$^2$·s with a total mass loss of 0.0210 lb/ft$^2$. The accumulated error in the surface energy balance is -0.00164 Btu/ft$^2$. Node number 1 is at 4381.8°F. The heating rate into the surface due to "QCHEM" is 740 Btu/ft$^2$·s and the total heating due to "CHEM" is 24.4 Btu/ft$^2$. There is no radiation from the surface. The recession rate is 0.0701 in/s with a total recession of 0.00227 inch. The heat imbalance for the present time step is 0.142 Btu/ft$^2$·s. The mass loss coefficient (BETA) equals 0.175. Heat conduction away from the surface is 3218.7 Btu/ft$^2$·s with an accumulated heat conduction loss of 104.6 Btu/ft$^2$. The sensible energy to increase the surface material from $T_2$ to $T_1$ is 446.2 Btu/ft$^2$·s with an accumulated value of 4.91 Btu/ft$^2$. The ratio of heat transfer coefficient with blowing to no blowing is 0.9359. The wall gases have an enthalpy ($\overline{H}_{rg,w}$) of 497.6 Btu/lb and the mass flow Stanton number is 3.706. The surface energy balance data is followed by temperature data. The temperature of each element is printed in degrees Fahrenheit. The final printout for this time step is the critical index number (6) and the critical time step (0.0112 second).

Surface temperature histories from this analysis are presented in Fig. 5. Notice the sawtooth effect caused by nodal lumping as the surface ablates. This sawtooth effect can be greatly reduced by using more elements near the surface. With smaller elements the true surface temperature will fall between the peaks and valleys of the CLAD curve presented in Fig. 5. Also shown in Fig. 5 are results from the one-dimensional CMA program (Ref. 3). CMA results are slightly lower because it uses a finite volume surface node while CLAD uses a zero volume node. Also note that because CMA drops nodes from the back surface it does not have any sawtoothing effect. The apparently better back node dropping technique is very difficult to implement in a three-dimensional node-dropping analysis and consequently was not used in CLAD.

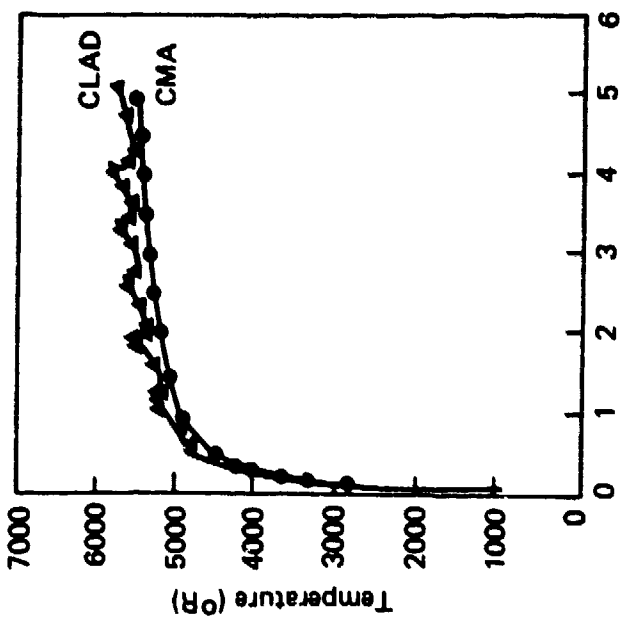


**Fig. 5 Sample Problem Surface Temperature Histories Using CLAD and CMA Computer Programs**

# 5. CONCLUSIONS AND RECOMMENDATIONS

A comprehensive computer program has been written to evaluate material damage to laser irradiated flight bodies. The CLAD program includes many features such as aerodynamic heating, radiation relief, and temperature dependent thermal properties that are also contained in similar laser damage computer programs. However, CLAD contains several unique features which are not generally included in the other programs (e.g., three-dimensional material removal, chemical reactions and vaporization at the surface, and in-depth melting). The combination of all these features into a single program provides an analytical tool that should be very useful in analyzing laser heated flight vehicles.

There are also several areas where CLAD can be expanded and improved. For example it could be expanded to include melt removal by aerodynamic shear forces at the surface or to include in-depth chemical reactions which occur in charring ablators.

The reader should also realize that the CLAD program was written for continuous wave laser applications, which have relatively low power densities compared with pulsed lasers. At the high intensities of a pulsed laser, ordinary thermal analysis no longer holds. Consequently the CLAD program will have to be extensively modified for application with pulsed lasers. These modifications are planned for the future.

Even without the above modifications, CLAD is still a powerful analytical tool for a wide range of laser heated material analyses.

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13. R. K. Frazer, "A Subroutine for Obtaining CalComp Plots of SHTP Variables," APL/JHU EM-4496, 13 December 1972.

14. R. K. Frazer, "Preliminary Calculations of Temperature and Ablation Histories for a Proposed Blast Tube Test at ARC," APL/JHU EM-4547, 7 January 1974.

## Appendix A

## DERIVATION OF EQUATION USED TO COMPUTE CHEMICAL HEATING RATE

The components of the chemical heating term in Eq. (1) are shown schematically in Fig. A-1. In Fig. A-1, gases diffuse through the boundary layer at a rate of ($m_d$) and have an average total enthalpy $\overline{H}_{dg,w}$. At the surface some of the gases react with the ablating material ($m_a$) and release chemical energy $q_{chem}$. The resulting gases then mix with the unreacted diffusion gases and form a gaseous mixture whose average total enthalpy is $\overline{H}_{rg,w}$. The resulting mixture leaves the surface via diffusion and convection at a rate of ($m_{rg}$). The rate of heat released at the surface is:

$$q_{chem} = m_d \overline{H}_{dg,w} + m_a H_{a,w} - m_{rg} \overline{H}_{rg,w} . \qquad (A-1)$$

Notice that all enthalpies in Eq. (A-1) are total enthalpies (i.e., they are the sum of the sensible and chemical enthalpies).

Obtaining Eq. (A-1) in the form shown in Eq. (5) of the text is accomplished as follows. Since there is no mass build-up at the surface and the mass flow out ($m_{rg}$) equals the mass flow in ($m_a + m_d$). Substituting for $m_{rg}$ in Eq. (A-1) and rearranging $q_{chem}$ results in:

$$q_{chem} = m_d (\overline{H}_{dg,w} - \overline{H}_{rg,w}) + m_a (H_{a,w} - \overline{H}_{rg,w}). \qquad (A-2)$$

However, $m_a$ can be defined by a parameter, $\beta$, where $m_a = \beta \rho_e U_e (C_m)_b$. For an informative discussion of the physical meaning of $\beta$, see Ref. 14.

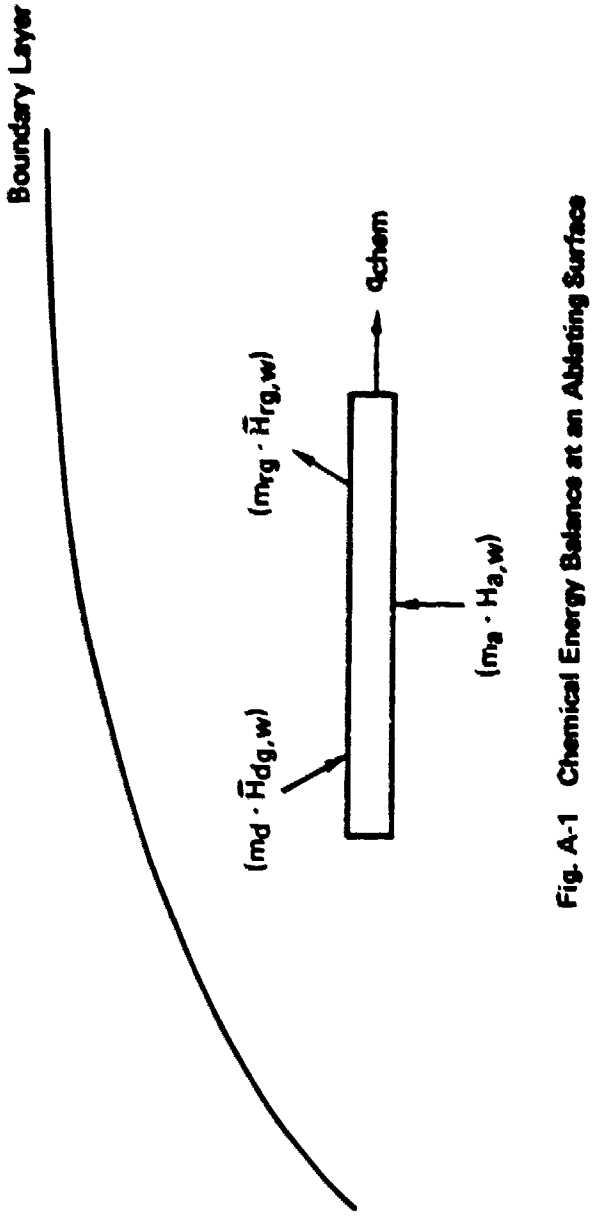


Fig. A-1 Chemical Energy Balance at an Ablating Surface

In Eq. (A-2) the total diffusion mass flow rate ($m_d$) arriving at the wall is the sum of the flow rates of individual species, each arriving at enthaly $H_{i,w}$ and, after chemical reaction, leaving at $\overline{H}_{rg,w}$. Hence, the energy term $m_d$ $(\overline{H}_{dg,w} - \overline{H}_{rg,w})$ in Eq. (A-1) becomes $\sum_{i=1}^{N} m_i (H_{i,w} - \overline{H}_{rg,w})$. Furthermore, according to Ref. 5, diffusion mass transfer can be related to concentration coefficients at the boundary layer edge ($Z_{i,e}$) and at the wall ($Z_{i,w}$) as follows:

$$\sum_{i=1}^{N} m_i = \rho_e U_e (C_m)_b \sum_{i=1}^{N} (Z_{i,e} - Z_{i,w}) . \qquad \text{(A-3)}$$

In addition, the enthalpy difference $(H_{i,w} - \overline{H}_{rg,w})$ is simply the chemical enthalpy change of each specie $(\Delta H_{i,w})$.

Hence, Eq. (A-2) becomes:

$$q_{chem} = \rho_e U_e (C_m)_b \sum_{i=1}^{N} (Z_{i,e} - Z_{i,w}) \Delta H_{i,w} + \beta (H_{a,w} - \overline{H}_{rg,w}) , \qquad \text{(A-4)}$$

which is in the form presented in Eq. (5).

## Appendix B

## MAIN PROGRAM FOR SAMPLE PROBLEM

This appendix presents the complete program used in analyzing the sample problem discussed in Section 4. The program contains the following comment statements which describe its overall organization.

```
/* DECLARE ENTRY STATEMENTS */

/* DECLARE VARIABLES */

/* ALLOCATE AND INITIALIZE VARIABLES */

/* READ INPUT DATA */

/* INITIALIZE MODEL TEMPERATURE */

/* STATEMENTS IN THE TIME STEP LOOP */

   ABARO

   CAPCN3

   WRITE

   STEP
```

The program is followed by input data.

```
  ABMAIN: PROC OPTIONS(MAIN) ;

/* DECLARE ENTRY STATEMENTS */
     DCL ABARO3 ENTRY  ( FIXED BIN, FIXED BIN,  FIXED BIN,
                                    FLOAT BIN,FLOAT BIN,
                         FLOAT BIN, FLOAT BIN, FLOAT BIN,
                         FLOAT BIN,
                         FLOAT BIN, FLOAT BIN, FIXED BIN, (*)FLOAT BIN,
                         FIXED BIN);
     DCL CAPCN3 ENTRY ;
     DCL DECIDE ENTRY(FLOAT BINARY, (*)FLOAT BINARY, (*)FLOAT BINARY )
                    RETURNS (FLOAT) ;
     DCL READAB ENTRY  (FIXED BIN, FIXED BIN, FLOAT BIN, FLOAT BIN,(*)
                    FLOAT BIN, (*)FLOAT BIN, FLOAT BIN,
                          FLOAT BIN, FLOAT BIN, FLOAT BIN,
                          FILE);
     DCL READFM ENTRY  (FIXED BIN, (*)FLOAT BIN, (*)FLOAT BIN,
                        (*)FLOAT BIN, (*)FLOAT BIN, (*)FLOAT BIN,
                        FIXED BIN, FILE);
     DCL READRK ENTRY  (FIXED BIN, (*)FLOAT BIN, (*)FLOAT BIN,
                        (*)FLOAT BIN, (*)FLOAT BIN, (*)FLOAT BIN,
                        FIXED BIN,FILE);
     DCL READTM ENTRY  ( FIXED BIN,
                        (*)FLOAT BIN, (*)FLOAT BIN, (*)FLOAT BIN,
                        (*)FLOAT BIN, (*)FLOAT BIN, (*)FLOAT BIN,
                        FIXED BIN, FILE);
     DCL REDCP3 ENTRY(FILE);
     DCL SET ENTRY( FLOAT BIN, FLOAT BIN, FLOAT BIN, FIXED BIN,
                   (*)FIXED BIN    , (*)FLOAT BIN ) ;
     DCL STEP ENTRY (FLOAT BIN,FLOAT BIN);
     DCL STORE  ENTRY(FIXED BIN,FIXED BIN,FIXED BIN);
     DCL WRITE ENTRY( (*)FLOAT BIN);

/* DECLARE VARIABLES */
        DCL SYSIN FILE;
        DCL ( ABS1(20),
              CP1(20),
              DELTIME,
              DUM1(14),
              DUMY(30),
              EMIS1(20),
              ENDTIME INIT(.5 ),
              FACTOR INIT(.5),
              HR1(30),
              K1(20),
              LAM INIT(.4),
              LEW# INIT(1.0),
              MAXSTP INIT(.5),
              MINSTP INIT(.005),
              PLTM1(30),
              QLIM INIT(.5),
```

```
                    QVAPOR(*) EXT CTL,
                    TVAP(*) CTL EXT,
                    QRAD(30),
                    RHOCH1(30),
                    RHOCP(13) INIT(18.89,18.89,33.3,42.95,48.8,
                          52.4,54.4,55.25,55.8,56.65,  57.55,58.45,563.84),
                    TEMPR(14) INIT(13.,   .001,560.,960.,1460.,1960.,
                         2460.,2960.,3460.,3960.,4460.,
                         4960.,10460.,11000.),
                    RO(*) EXT CTL,
                    T1(21), T2(21),T3(21),
                    TIME1 (31),
                    TIMEP(30),
                    TINC INIT(100),
                    TINIT INIT(540.),
                    TLIM INIT(.1),
                    TMAX INIT ( 9000),
                    TMIN INIT(500),
                    TR1(10) INIT((10)0.0),
                    TREF EXT INIT(536.),
                    TSP INIT(.0001),
                    TZERO INIT(.20),
                    VIEW INIT(1.)) FLOAT BIN;

               DCL( CYL INIT(-1),
                    I,
                    ITLIM INIT(10),
                    INPUT INIT(1),
                    #SURF INIT(1),
                    #BETA INIT(39),
                    #PL INIT( 2),
                    LASCAP INIT( 18),
                    N1 INIT(13),
                    N4 INIT( 5),
                    N6 INIT(20),
                    NDEXR(10) INIT((10)300),
                    NMAT INIT(1),
                    PLTCODE INIT(0),
                    AIRPRNT EXT INIT(1),
                    NTS INIT(0)) FIXED BIN;

/* ALLOCATE AND INITALIZE VARIABLES */
       ALLOCATE RO(9),QVAPOR(9),TVAP(9);
       GET COPY DATA;
       CALL STORE (LASCAP,LASCAP,3);

     DELTIME = (ENDTIME-TZERO)/N6;
     DO I = 1 TO N6+1;
      TIMEP(I)= TZERO+ (I-1)*DELTIME;
     END;
```

```
/* READ INPUT DATA */
      PUT LIST (' MATERIAL  HEAT OF VAP(BTU/FT**3)      MELT TEMP
  DENSITY');
            DO I = 1 TO NMAT;
            GET LIST (QVAPOR(I),TVAP(I),RO(I));
             PUT EDIT(I,QVAPOR(I),TVAP(I),RO(I))
                (SKIP,F(6),E(20,3),F(19,2),E(20,3),F(19,2),E(20,3));
            END;
      CALL READRK(1,T1,CP1,K1,EMIS1,ABS1,N1,SYSIN);
      CALL READTM (1,TIME1, HR1, QRAD, RHOCH1, PH.TM1, DUMY,N4,SYSIN);
      CALL READAB ( #PL, #BETA, LEW#,RO(1),RHOCP,TEMPR,
                    TMIN, TMAX, TINC, 1.8,        SYSIN);
      CALL REDCP3(SYSIN);

/* INITIALIZE MODEL TEMPERATURE */
      CALL SET(TZERO,ENDTIME,TINIT,NTS,NDEXP,TR1);

/* STATEMENTS IN THE TIME STEP LOOP */
 IMX: CALL ABAR03(1,#SURF,CYL, LAM,TSP, 1.1,VIEW, FACTOR,
                  TLIM,QLIM,ITLIM,  TIMEP,PLTCODE);
      CALL CAPCN3;
      CALL WRITE(TIMEP);
      CALL STEP(MINSTP,MAXSTP);
      GO TO IMX;
      END ABMAIN;
```

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```
NTS= 10  TR1(1)=3025.  NDEXR(1)=2     TR1(2)=1274.  NDEXR(2)=3
         TR1(3)=961.   NDEXR(3)=4     TR1(4)=795.   NDEXR(4)=5
         TR1(5)=699.   NDEXR(5)=6     TR1(6)=640.   NDEXR(6)=7
         TR1(7)=587.   NDEXR(7)=8     TR1(8)=557.   NDEXR(8)=9
         TR1(9)=546.   NDEXR(9)=10       TR1(10)=542.  NDEXR(10)=11
    $
              4000.    0.0   111.
        THERMAL PROPERTIES OF ATJ - S RHO CP SAME AS POCO
 TEMP  DEG R       RHOCP              K                  EMISS        AHS024
      0.           18.89           58.00          0.0             0.0
    560.           18.89           72.00
    960.           33.30           53.70
   1460.           42.95           41.20
   1960.           48.80           32.10
   2460.           52.40           25.20
   2960.           54.40           20.00
   3460.           55.25           17.10
   3960.           55.80           15.40
   4460.           56.60           15.40
   4960.           57.50           16.60
  10460.           58.45           18.75
 21000.            58.45           18.75
                HEATING   PARAMETERS   AMC -  ATJ  STUDY
 TIME      REC ENTH      RADIN      CONV CM     P LOC      DUMMY
   0.0      1287.         0.0       3.95967    100.001
   0.1      1287.         0.0       3.95967    100.001
  10.       1287.         0.0       3.95967    100.001
  13.       1287.         0.0       3.95967    100.001
  15.       1287.         0.0       3.95967    100.001
 ENTHALPY DATA FOR ATJ-S AND AIR
LOCAL PRESS      BETA          TW          HW
  100.00000      0.00001     298.19995      1.00000
  100.00000      0.00002     599.00000    150.50000
  100.00000      0.00270    1000.00000    154.20000
  100.00000      0.01930    1100.00000     60.39999
  100.00000      0.04290    1150.00000    -98.39999
  100.00000      0.08130    1200.00000   -369.09985
  100.00000      0.12520    1250.00000   -238.50000
  100.00000      0.16860    1350.00000    -62.89999
  100.00000      0.17430    1450.00000    -15.30000
  100.00000      0.17480    1666.66992     51.09999
  100.00000      0.17491    2200.07446    208.59000
  100.00000      0.17500    2627.85840    348.92383
  100.00000      0.17600    3100.89258    503.05884
  100.00000      0.17800    3355.70850    594.13599
  100.00000      0.18000    3647.02137    696.(3281
  100.00000      0.19000    3785.44877    797.61597
  100.00000      0.20000    3926.84399    899.13696
  100.00000      0.35000    4446.30469   1913.29492
  100.00000      0.50000    4597.35156   2451.33398
  100.00000      1.00000    4796.43359   3819.44191
  100.00000      2.00000    4926.94648   5136.42969
  100.00000      2.50000    4957.05469   5505.51953
  100.00000      3.00000    4974.13672   5774.50781
```

| | | | |
|---|---|---|---|
| 100.00000 | 3.50000 | 4995.74609 | 5991.03125 |
| 100.00000 | 4.00000 | 5008.71094 | 6159.15625 |
| 100.00000 | 4.50000 | 5019.14453 | 6295.91797 |
| 100.00000 | 5.00000 | 5027.73047 | 6409.29688 |
| 100.00000 | 5.50000 | 5034.93359 | 6504.74953 |
| 100.00000 | 6.00000 | 5041.05859 | 6586.23047 |
| 100.00000 | 6.50000 | 5046.33594 | 6656.53516 |
| 100.00000 | 7.00000 | 5050.93750 | 6717.82422 |
| 100.00000 | 7.50000 | 5054.99219 | 6771.70313 |
| 100.00000 | 8.00000 | 5058.59594 | 6819.43750 |
| 100.00000 | 10.00000 | 5069.67578 | 6965.83594 |
| 100.00000 | 15.00000 | 5085.27344 | 7169.13281 |
| 100.00000 | 20.00000 | 5093.54297 | 7271.85156 |
| 100.00000 | 30.00000 | 5102.23438 | 7376.56641 |
| 100.00000 | 40.00000 | 5106.79516 | 7428.92578 |
| 100.00000 | 50.00000 | 5109.60938 | 7460.19141 |
| 500.00000 | 0.00001 | 298.19995 | 1.00000 |
| 500.00000 | 0.00002 | 999.00000 | 100.50000 |
| 500.00000 | 0.00270 | 1000.00000 | 159.20000 |
| 500.00000 | 0.01930 | 1100.00000 | 60.39994 |
| 500.00000 | 0.04290 | 1150.00000 | -98.39994 |
| 500.00000 | 0.08130 | 1200.00000 | -349.69995 |
| 500.00000 | 0.12520 | 1250.00000 | -238.50000 |
| 500.00000 | 0.16950 | 1350.00000 | -62.89999 |
| 500.00000 | 0.17430 | 1450.00000 | -15.30000 |
| 500.00000 | 0.17480 | 1666.66992 | 51.09994 |
| 500.00000 | 0.17491 | 2300.00122 | 239.98444 |
| 500.00000 | 0.17500 | 2715.06519 | 376.40795 |
| 500.00000 | 0.17600 | 3146.93018 | 517.08496 |
| 500.00000 | 0.17800 | 3423.68140 | 613.83276 |
| 500.00000 | 0.18000 | 3572.46826 | 670.54077 |
| 500.00000 | 0.19000 | 3928.60938 | 833.96191 |
| 500.00000 | 0.20000 | 4106.16406 | 942.57178 |
| 500.00000 | 0.35000 | 4740.66016 | 1889.62988 |
| 500.00000 | 0.50000 | 4975.63672 | 2542.56396 |
| 500.00000 | 1.00000 | 5229.51563 | 3938.62793 |
| 500.00000 | 2.00000 | 5392.87109 | 5279.68750 |
| 500.00000 | 2.50000 | 5431.80859 | 5654.36328 |
| 500.00000 | 3.00000 | 5459.35938 | 5932.66894 |
| 500.00000 | 3.50000 | 5480.10938 | 6147.08594 |
| 500.00000 | 4.00000 | 5496.30859 | 6317.56641 |
| 500.00000 | 4.50000 | 5509.32813 | 6456.16797 |
| 500.00000 | 5.00000 | 5520.05078 | 6571.01953 |
| 500.00000 | 5.50000 | 5529.01953 | 6667.66797 |
| 500.00000 | 6.00000 | 5536.66797 | 6750.10547 |
| 500.00000 | 6.50000 | 5543.25391 | 6821.23438 |
| 500.00000 | 7.00000 | 5548.99609 | 6883.21875 |
| 500.00000 | 7.50000 | 5554.04688 | 6937.66797 |
| 500.0000 | 8.00000 | 5558.5273 | 6985.891 |
| 500.0000 | 10.00000 | 5572.3359 | 7139.691 |
| 500.0000 | 15.00000 | 5591.7930 | 7337.598 |
| 500.0000 | 20.00000 | 5602.109 | 7441.941 |
| 500.0000 | 30.00000 | 5612.945 | 7547.082 |
| 500.0000 | 40.00000 | 5618.629 | 7599.555 |
| 500.0000 | 50.00000 | 5622.14 | 7630.832 |

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GEOMETRY(HEATED INTERNAL SURFACE ELEMENT #1)

| I | V/L | | MAT | #CON | I2 | A/L | I3 | A/L |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.0F0 | 1. | 1. | 2. | | 17.895F0 | 0.0 | 0.0F0 |
| 0.0 | 0.0F0 | 0.0 | 0.0E0 | | | | | |
| 2 | 1.5973E-4 | 1. | 1.0 | 3.0 | | 9.6918E0 | 0.0 | 0.0F0 |
| 0.0 | 0.0E0 | 0.0 | 0.0E0 | | | | | |
| 3 | 1.7709E-4 | 1. | 1.0 | 4.0 | | 1.0693E1 | 0.0 | 0.0E0 |
| 0.0 | 0.0F0 | 0.0 | 0.0F0 | | | | | |
| 4 | 1.9445E-4 | 1. | 1.0 | 5.0 | | 1.1693E1 | 0.0 | 0.0E0 |
| 0.0 | 0.0E0 | 0.0 | 0.0E0 | | | | | |
| 5 | 2.1181F-4 | 1. | 1.0 | 6.0 | | 1.2693E1 | 0.0 | 0.0E0 |
| 0.0 | 0.0F0 | 0.0 | 0.0E0 | | | | | |
| 6 | 2.2917E-4 | 1. | 1.0 | 7.0 | | 1.3693E1 | 0.0 | 0.0E0 |
| 0.0 | 0.0E0 | 0.0 | 0.0E0 | | | | | |
| 7 | 2.4653E-4 | 1. | 1.0 | 8.0 | | 9.9585F0 | 0.0 | 0.0E0 |
| 0.0 | 0.0E0 | 0.0 | 0.0E0 | | | | | |
| 8 | 5.4514E-4 | 1. | 1.0 | 9.0 | | 8.3401E0 | 0.0 | 0.0E0 |
| 0.0 | 0.0F0 | 0.0 | 0.0E0 | | | | | |
| 9. | 6.1459E-4 | 1. | 1.0 | 10. | | 9.3411F0 | 0.0 | 0.0E0 |
| 0.0 | 0.0F0 | 0.0 | 0.0E0 | | | | | |
| 10 | 6.8403E-4 | 1. | 1.0 | 11. | | 1.0342E1 | 0.0 | 0.0E0 |
| 0.0 | 0.0E0 | 0.0 | 0.0E0 | | | | | |
| 11 | 7.5348E-4 | 1. | 1.0 | 12. | | 1.1343E1 | 0.0 | 0.0E0 |
| 0.0 | 0.0F0 | 0.0 | 0.0E0 | | | | | |
| 12. | 8.2292E-4 | 1. | 1.0 | 13. | | 1.2343E1 | 0.0 | 0.0E0 |
| 0.0 | 0.0E0 | 0.0 | 0.0E0 | | | | | |
| 13. | 8.9236E-4 | 1. | 1.0 | 14. | | 1.3344F1 | 0.0 | 0.0E0 |
| 0.0 | 0.0E0 | 0.0 | 0.0E0 | | | | | |
| 14. | 9.6181E-4 | 1. | 1.0 | 15. | | 1.4344E1 | 0.0 | 0.0E0 |
| 0.0 | 0.0F0 | 0.0 | 0.0F0 | | | | | |
| 15. | 1.0312E-3 | 1. | 1.0 | 16. | | 1.5345E1 | 0.0 | 0.0E0 |
| 0.0 | 0.0F0 | 0.0 | 0.0E0 | | | | | |
| 16. | 1.1007E-3 | 1. | 1.0 | 17. | | 1.6345F1 | 0.0 | 0.0E0 |
| 0.0 | 0.0E0 | 0.0 | 0.0E0 | | | | | |
| 17. | 1.1701E-3 | 1. | 1.0 | 18. | | 1.1726F1 | 0.0 | 0.0E0 |
| 0.0 | 0.0F0 | 0.0 | 0.0E0 | | | | | |
| 18. | 1.2396E-3 | 1. | 1.0 | 0.0 | | 0.0E0 | 0.0 | 0.0E0 |
| 0.0 | 0.0E0 | 0.0 | 0.0F0 | | | | | |

SURFACE AREA AND RADIUS DATA FOR ARARO3 #1

| SURFACE ELEMENT | AREA(FT**2) | RADIUS(FT) |
|---|---|---|
| 1 | .03625 | .03625 |

# Appendix C

## SAMPLE PROBLEM PRINTOUT

A portion of the sample problem printout is presented in this appendix. The first page contains data read into the main procedure via GET statements and READ subroutines. The next five pages contain thermochemical tables for ATJ-S graphite and air, and are followed by two tables defining the model geometry. The remaining pages present typical printouts at 0.2 second, 0.221 second, and 0.232 second. The time-dependent output is divided into aerodynamic heating data, surface energy balance information, thermal capacitor temperatures, and critical time step data.

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```
NTS= 1   TR1(1)=3025.   NDEXR(1)=2    TR1(2)=1274.   NDEXR(2)=3
         TR1(3)=961.    NDEXR(3)=4    TR1(4)=795.    NDEXR(4)=5
         TR1(5)=699.    NDEXR(5)=6    TR1(6)=640.    NDEXR(6)=7
         TR1(7)=587.    NDEXR(7)=8    TR1(8)=557.    NDEXR(8)=9
         TR1(9)=546.    NDEXR(9)=10     TR1(10)=542.  NDEXR(10)=11
      :
MATERIAL  HEAT OF VAP(BTU/FT**3)        MELT TEMP        DENSITY
   1            4.003E+03                 0.00          1.110E+02
```

THE DATA FOR READRK STATEMENT # 1:
THERMAL PROPERTIES OF ATJ - S RHO CP SAME AS POCO

| TEMP DEG R | RHOCP | K | EMISS | ABSORB |
|---|---|---|---|---|
| 0.000 | 1[illegible].600 | 58.000 | 0.000 | 0.000 |
| 560.000 | 18.990 | 72.200 | 0.000 | 0.000 |
| 960.000 | 33.360 | 52.700 | 0.000 | 0.000 |
| 1460.000 | 42.960 | 41.200 | 0.000 | 0.000 |
| 1960.000 | 46.560 | 32.100 | 0.000 | 0.000 |
| 2460.000 | 52.400 | 24.200 | 0.000 | 0.000 |
| 2960.000 | 54.600 | 20.000 | 0.000 | 0.000 |
| 3460.000 | 55.250 | 17.100 | 0.000 | 0.000 |
| 3960.000 | 55.800 | 15.400 | 0.000 | 0.000 |
| 4460.000 | 56.600 | 15.400 | 0.000 | 0.000 |
| 4960.000 | 57.500 | 16.400 | 0.000 | 0.000 |
| 10460.000 | 58.450 | 18.750 | 0.000 | 0.000 |
| 21000.000 | 58.450 | 18.750 | 0.000 | 0.000 |

THE DATA FOR READTH STATEMENT # 1
HEATING PARAMETERS ABC - ATJ STUDY

| TIME | REC ENTH | RADTH | CONV CH | P LOC | DUMMY |
|---|---|---|---|---|---|
| 0.000 | 1287.000 | 0.000 | 3.960 | 100.001 | 0.000 |
| 0.100 | 1287.000 | 0.000 | 3.960 | 100.001 | 0.000 |
| 10.000 | 1287.000 | 0.000 | 3.960 | 100.001 | 0.000 |
| 13.000 | 1287.000 | 0.000 | 3.960 | 100.001 | 0.000 |
| 15.000 | 1287.000 | 0.000 | 3.960 | 100.001 | 0.000 |

THE ENTHALPY VALUES IN THE THERMOCHEMICAL DATA HAVE BEEN REFERENCED TO 536.00 DEGREES RANKINE.

CALCULATED VALUES OF SURFACE MATERIAL ENTHALPY

| TEMP - R | ENTHALPY |
|---|---|
| 0.001 | -91.216 |
| 560.000 | 0.094 |
| 960.000 | 98.123 |
| 1460.000 | 269.854 |
| 1960.000 | 474.498 |
| 2460.000 | 704.426 |
| 2960.000 | 944.457 |
| 3460.000 | 1191.924 |
| 3960.000 | 1442.038 |
| 4460.000 | 1695.304 |
| 4960.000 | 1952.311 |
| 10460.000 | 4526.343 |
| 11000.000 | 6340.354 |

ENTHALPY DATA FOR ATJ-S AND AIR

| P LOCAL | BETA | T WALL | H WALL | Q CHEM |
|---|---|---|---|---|
| 100.00000 | 0.00001 | 534.76 | 1.7000006+00 | -1.6728646-05 |
| 100.00300 | 0.00002 | 1798.20 | 3.7489076+02 | 1.6045796-03 |
| 100.00900 | 0.00275 | 1800.00 | 2.8655986+02 | 3.3429246-01 |
| 100.00300 | 0.01933 | 1950.00 | 1.8971006+07 | 7.2740736+00 |
| 100.00000 | 0.04290 | 2070.00 | -1.7711006+02 | 3.0191396+01 |
| 100.00000 | 0.08130 | 2160.00 | -6.2837096+02 | 9.7235636+01 |
| 100.00000 | 0.12520 | 2250.00 | -4.2070006+07 | 1.2005796+02 |
| 100.00900 | 0.16960 | 2430.00 | -1.1321006+07 | 1.3554936+02 |
| 100.00000 | 0.17430 | 2610.00 | -2.7530006+01 | 1.4015966+02 |
| 100.00000 | 0.17490 | 3006.00 | 9.1879006+01 | 1.5255586+02 |
| 100.00300 | 0.17491 | 3960.13 | 3.7566176+02 | 1.6454656+02 |
| 100.00000 | 0.17530 | 4730.14 | 6.7876256+02 | 2.1103506+02 |
| 100.00300 | 0.17630 | 5581.60 | 9.9550546+02 | 2.6143796+02 |
| 100.00000 | 0.17800 | 6040.27 | 1.0596446+03 | 2.5766046+02 |
| 100.00000 | 0.18000 | 6276.63 | 1.1639396+03 | 2.6577766+02 |
| 100.00000 | 0.19000 | 6513.88 | 1.4357096+03 | 2.8224376+02 |
| 100.00000 | 0.20000 | 7068.31 | 1.4194446+03 | 2.8714096+02 |
| 100.00000 | 0.35000 | 8003.34 | 3.7538706+03 | 9.7578536+01 |
| 100.00000 | 0.50000 | 8275.22 | 4.4123906+03 | -3.0389626+02 |
| 100.00000 | 1.00000 | 8633.57 | 4.8752276+03 | -3.0029876+03 |
| 100.00000 | 2.00000 | 8844.88 | 9.2444696+03 | -1.0505056+04 |
| 100.00000 | 2.50000 | 8922.59 | 9.8000226+03 | -1.4717046+04 |
| 100.00000 | 3.00000 | 8962.44 | 1.0403156+04 | -1.9077656+04 |
| 100.00000 | 3.50000 | 8992.33 | 1.0779856+04 | -2.3535746+04 |
| 100.00000 | 4.00000 | 9015.48 | 1.1084476+04 | -2.8059136+04 |
| 100.00000 | 4.50000 | 9034.45 | 1.1332646+04 | -3.2630136+04 |
| 100.00000 | 5.00000 | 9049.91 | 1.1536736+04 | -3.7235726+04 |
| 100.00000 | 5.50000 | 9062.87 | 1.1706576+04 | -4.1867226+04 |
| 100.00000 | 6.00000 | 9073.89 | 1.1855216+04 | -4.6518596+04 |
| 100.00000 | 6.50000 | 9083.40 | 1.1991756+04 | -5.1184446+04 |
| 100.00000 | 7.00000 | 9091.48 | 1.2098286+04 | -5.5844706+04 |
| 100.00000 | 7.50000 | 9098.98 | 1.2179066+04 | -6.0553506+04 |
| 100.00000 | 8.00000 | 9105.45 | 1.2274986+04 | -6.5251.66+04 |
| 100.00000 | 10.00000 | 9125.40 | 1.2538506+04 | -8.4096466+04 |
| 100.00000 | 15.00000 | 9153.69 | 1.2902636+04 | -1.3138306+05 |
| 100.00000 | 20.00000 | 9168.37 | 1.3089326+04 | -1.7875486+05 |
| 100.00000 | 30.00000 | 9184.02 | 1.3277316+04 | -2.7354486+05 |
| 100.00000 | 40.00000 | 9192.21 | 1.3372056+04 | -3.6832436+05 |
| 100.00000 | 50.00000 | 9197.29 | 1.3429346+04 | -4.6308726+05 |

| LOG10(P LOCAL) | WALL TEMP | H WALL | QCHEM |
|---|---|---|---|
| 2.00000 | 500.00 | 1.5470946+00 | 0.0000006+00 |
| 2.00100 | 600.00 | 2.3356606+00 | 0.0000006+00 |
| 2.00000 | 700.00 | 3.5259736+00 | 0.0000006+00 |
| 2.00000 | 800.00 | 5.3239416+00 | 0.0000006+00 |
| 2.00000 | 900.00 | 8.0384126+00 | 0.0000006+00 |
| 2.00300 | 1000.00 | 1.2151706+01 | 0.0000006+00 |
| 2.00000 | 1100.00 | 1.8314906+01 | 0.0000006+00 |
| 2.00000 | 1200.00 | 2.7649266+01 | 0.0000006+00 |
| 2.00000 | 1300.00 | 4.1741156+01 | 0.0000006+00 |
| 2.00000 | 1400.00 | 6.3015236+01 | 0.0000006+00 |
| 2.00000 | 1500.00 | 9.5131416+01 | 0.0000006+00 |
| 2.00000 | 1600.00 | 1.4361756+02 | 0.0000006+00 |
| 2.00000 | 1700.00 | 2.1686446+02 | 0.0000006+00 |
| 2.00000 | 1800.00 | 2.2555236+02 | 1.0000126+00 |
| 2.00000 | 1900.00 | 1.4723436+02 | 3.9114076+00 |
| 2.00000 | 2000.00 | 1.2137466+01 | 0.0000006+00 |
| 2.00000 | 2100.00 | -2.7014146+02 | 4.4584886+01 |



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| | | | |
|---|---|---|---|
| 2.00000 | 2200.00 | -5.304954E+02 | 1.106172E+02 |
| 2.00000 | 2300.00 | -2.964622E+02 | 1.314848E+02 |
| 2.00000 | 2400.00 | -1.413813E+02 | 1.344098E+02 |
| 2.00000 | 2500.00 | -6.533658E+01 | 1.373238E+02 |
| 2.00000 | 2600.00 | -2.978986E+01 | 1.398891E+02 |
| 2.00000 | 2700.00 | -4.513403E+00 | 1.429275E+02 |
| 2.00000 | 2800.00 | 1.652786E+00 | 1.449674E+02 |
| 2.00000 | 2900.00 | 1.232927E+01 | 1.492762E+02 |
| 2.00000 | 3000.00 | 9.197255E+01 | 1.525557E+02 |
| 2.00000 | 3100.00 | 1.064914E+02 | 1.557871E+02 |
| 2.00000 | 3200.00 | 1.232930E+02 | 1.590872E+02 |
| 2.00000 | 3300.00 | 1.427455E+02 | 1.624571E+02 |
| 2.00000 | 3400.00 | 1.652673E+02 | 1.658983E+02 |
| 2.00000 | 3500.00 | 1.913422E+02 | 1.694125E+02 |
| 2.00000 | 3600.00 | 2.215312E+02 | 1.730012E+02 |
| 2.00000 | 3700.00 | 2.564832E+02 | 1.766657E+02 |
| 2.00000 | 3800.00 | 2.969560E+02 | 1.804080E+02 |
| 2.00000 | 3900.00 | 3.438010E+02 | 1.842296E+02 |
| 2.00000 | 4000.00 | 3.855974E+02 | 1.877429E+02 |
| 2.00000 | 4100.00 | 4.122415E+02 | 1.907981E+02 |
| 2.00000 | 4200.00 | 4.467266E+02 | 1.938624E+02 |
| 2.00000 | 4300.00 | 4.711799E+02 | 1.970164E+02 |
| 2.00000 | 4400.00 | 5.037371E+02 | 2.002914E+02 |
| 2.00000 | 4500.00 | 5.369444E+02 | 2.036378E+02 |
| 2.00000 | 4600.00 | 5.757588E+02 | 2.067264E+02 |
| 2.00000 | 4700.00 | 6.155405E+02 | 2.100489E+02 |
| 2.00000 | 4800.00 | 6.472007E+02 | 2.134259E+02 |
| 2.00000 | 4900.00 | 6.756155E+02 | 2.169196E+02 |
| 2.00000 | 5000.00 | 7.052778E+02 | 2.202678E+02 |
| 2.00000 | 5100.00 | 7.362627E+02 | 2.237709E+02 |
| 2.00000 | 5200.00 | 7.689647E+02 | 2.273297E+02 |
| 2.00000 | 5300.00 | 8.023101E+02 | 2.309450E+02 |
| 2.00000 | 5400.00 | 8.375349E+02 | 2.346179E+02 |
| 2.00000 | 5500.00 | 8.743044E+02 | 2.383492E+02 |
| 2.00000 | 5600.00 | 9.115761E+02 | 2.420685E+02 |
| 2.00000 | 5700.00 | 9.452478E+02 | 2.459249E+02 |
| 2.00000 | 5800.00 | 9.851699E+02 | 2.497307E+02 |
| 2.00000 | 5900.00 | 1.016383E+03 | 2.575867E+02 |
| 2.00000 | 6000.00 | 1.053933E+03 | 2.594192E+02 |
| 2.00000 | 6100.00 | 1.092573E+03 | 2.596490E+02 |
| 2.00000 | 6200.00 | 1.132421E+03 | 2.631107E+02 |
| 2.00000 | 6300.00 | 1.174610E+03 | 2.666731E+02 |
| 2.00000 | 6400.00 | 1.221399E+03 | 2.696714E+02 |
| 2.00000 | 6500.00 | 1.270051E+03 | 2.725037E+02 |
| 2.00000 | 6600.00 | 1.320642E+03 | 2.755696E+02 |
| 2.00000 | 6700.00 | 1.373248E+03 | 2.786702E+02 |
| 2.00000 | 6800.00 | 1.427949E+03 | 2.818050E+02 |
| 2.00000 | 6900.00 | 1.485128E+03 | 2.838918E+02 |
| 2.00000 | 7000.00 | 1.567214E+03 | 2.858170E+02 |
| 2.00000 | 7100.00 | 1.657379E+03 | 2.748279E+02 |
| 2.00000 | 7200.00 | 1.786499E+03 | 2.644687E+02 |
| 2.00000 | 7300.00 | 1.925679E+03 | 2.197594E+02 |
| 2.00000 | 7400.00 | 2.075702E+03 | 1.958017E+02 |
| 2.00000 | 7500.00 | 2.237411E+03 | 1.744558E+02 |
| 2.00000 | 7600.00 | 2.411720E+03 | 1.594370E+02 |
| 2.00000 | 7700.00 | 2.599609E+03 | 1.384918E+02 |
| 2.00000 | 7800.00 | 2.802135E+03 | 1.239936E+02 |
| 2.00000 | 7900.00 | 3.020437E+03 | 1.099415E+02 |
| 2.00000 | 8000.00 | 3.255769E+03 | 9.799481E+01 |
| 2.00000 | 8100.00 | 3.633204E+03 | 2.353269E+00 |

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THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
SILVER SPRING, MARYLAND

ENTHALPY DATA FOR ATJ-S AND AIR

| P LOCAL | BETA | T WALL | H WALL | Q CHFM |
|---|---|---|---|---|
| 500.00000 | 0.00001 | 536.76 | 1.7000000E+00 | -1.6708646E-05 |
| 500.00000 | 0.00002 | 1798.20 | 3.2489078E+02 | 1.6945705E-03 |
| 500.00000 | 0.00273 | 1800.00 | 2.8659088E+02 | 3.3429246E-01 |
| 500.00000 | 0.01933 | 1980.00 | 1.0871008E+02 | 7.2740736E+00 |
| 500.00000 | 0.04290 | 2070.00 | -1.7711998E+02 | 3.0191288E+01 |
| 500.00000 | 0.06130 | 2160.00 | -6.2837898E+02 | 6.7239638E+01 |
| 500.00000 | 0.12570 | 2250.00 | -4.7929988E+02 | 1.2995708E+02 |
| 500.00000 | 0.16860 | 2430.00 | -1.1321998E+02 | 1.3554038E+02 |
| 500.00000 | 0.17430 | 2610.00 | -2.7539988E+01 | 1.4015948E+02 |
| 500.00000 | 0.17490 | 3000.00 | 9.1979998E+01 | 1.5255558E+02 |
| 500.00000 | 0.17491 | 4140.00 | 4.3197278E+02 | 1.9261838E+02 |
| 500.00000 | 0.17533 | 4827.11 | 6.7755398E+02 | 2.1655948E+02 |
| 500.00000 | 0.17533 | 5664.47 | 9.3075238E+02 | 2.4461528E+02 |
| 500.00000 | 0.17600 | 6167.62 | 1.1048988E+03 | 2.6272058E+02 |
| 500.00000 | 0.18000 | 6430.44 | 1.2048728E+03 | 2.7240738E+02 |
| 500.00000 | 0.19000 | 7071.49 | 1.5011238E+03 | 2.9538968E+02 |
| 500.00000 | 0.20000 | 7391.08 | 1.6044298E+03 | 3.0523518E+02 |
| 500.00000 | 0.35000 | 8605.19 | 3.4013328E+03 | 1.5955378E+02 |
| 500.00000 | 0.50000 | 8956.16 | 4.5746808E+03 | -2.6801368E+02 |
| 500.00000 | 1.00000 | 9413.17 | 7.0895238E+03 | -2.6101638E+03 |
| 500.00000 | 2.00000 | 9707.16 | 9.5036308E+03 | -1.0140858E+04 |
| 500.00000 | 2.50000 | 9777.24 | 1.0177468E+04 | -1.4279568E+04 |
| 500.00000 | 3.00000 | 9826.84 | 1.0578478E+04 | -1.8548658E+04 |
| 500.00000 | 3.50000 | 9864.19 | 1.1044798E+04 | -2.2923918E+04 |
| 500.00000 | 4.00000 | 9893.34 | 1.1371418E+04 | -2.7365308E+04 |
| 500.00000 | 4.50000 | 9916.79 | 1.1621038E+04 | -3.1853508E+04 |
| 500.00000 | 5.00000 | 9936.08 | 1.1827878E+04 | -3.6374038E+04 |
| 500.00000 | 5.50000 | 9952.22 | 1.2001808E+04 | -4.0926038E+04 |
| 500.00000 | 6.00000 | 9966.00 | 1.2159188E+04 | -4.5491548E+04 |
| 500.00000 | 6.50000 | 9977.85 | 1.2279218E+04 | -5.0074688E+04 |
| 500.00000 | 7.00000 | 9988.18 | 1.2388778E+04 | -5.4669518E+04 |
| 500.00000 | 7.50000 | 9997.28 | 1.2497888E+04 | -5.9272998E+04 |
| 500.00000 | 8.00000 | 10005.34 | 1.2577648E+04 | -6.3884218E+04 |
| 500.00000 | 10.00000 | 10030.19 | 1.2946638E+04 | -8.2389318E+04 |
| 500.00000 | 15.00000 | 10065.22 | 1.3307678E+04 | -1.2861348E+05 |
| 500.00000 | 20.00000 | 10083.79 | 1.3398488E+04 | -1.7531368E+05 |
| 500.00000 | 30.00000 | 10103.29 | 1.3588738E+04 | -2.6923238E+05 |
| 500.00000 | 40.00000 | 10113.53 | 1.3679198E+04 | -3.6135418E+05 |
| 500.00000 | 50.00000 | 10119.84 | 1.3735498E+04 | -4.5434228E+05 |

| LOG10(P LOCAL) | WALL TEMP | H WALL | QCHFM |
|---|---|---|---|
| 2.69897 | 500.00 | 1.4470968E+00 | 0.0000008E+00 |
| 2.69897 | 600.00 | 2.3356008E+00 | 0.0000008E+00 |
| 2.69897 | 700.00 | 3.5259738E+00 | 0.0000008E+00 |
| 2.69897 | 800.00 | 5.3230418E+00 | 0.0000008E+00 |
| 2.69897 | 900.00 | 8.0340128E+00 | 0.0000008E+00 |
| 2.69897 | 1000.00 | 1.2131708E+01 | 0.0000008E+00 |
| 2.69897 | 1100.00 | 1.8314808E+01 | 0.0000008E+00 |
| 2.69897 | 1200.00 | 2.7649268E+01 | 0.0000008E+00 |
| 2.69897 | 1300.00 | 4.1741158E+01 | 0.0000008E+00 |
| 2.69897 | 1400.00 | 6.3015238E+01 | 0.0000008E+00 |
| 2.69897 | 1500.00 | 9.5131918E+01 | 0.0000008E+00 |
| 2.69897 | 1600.00 | 1.4361758E+02 | 0.0000008E+00 |
| 2.69897 | 1700.00 | 2.1681448E+02 | 0.0000008E+00 |
| 2.69897 | 1800.00 | 2.8655638E+02 | 1.0000108E+00 |
| 2.69897 | 1900.00 | 1.6725388E+02 | 9.0114078E+00 |
| 2.69897 | 2000.00 | 1.2137068E+01 | 9.8872368E+00 |
| 2.69897 | 2100.00 | -2.7014148E+02 | 4.6586488E+01 |

| | | | |
|---|---|---|---|
| 2.69897 | 2200.00 | -5.304954E+02 | 1.106172E+02 |
| 2.69897 | 2300.00 | -2.964622E+02 | 1.214868E+02 |
| 2.69897 | 2400.00 | -1.412813E+02 | 1.244108E+02 |
| 2.69897 | 2500.00 | -6.533656E+01 | 1.273238E+02 |
| 2.69897 | 2600.00 | -2.978986E+01 | 1.298991E+02 |
| 2.69897 | 2700.00 | -4.513403E+00 | 1.429275E+02 |
| 2.69897 | 2800.00 | 1.452786E+00 | 1.440674E+02 |
| 2.69897 | 2900.00 | 1.232927E+01 | 1.492762E+02 |
| 2.69897 | 3000.00 | 9.197255E+01 | 1.525567E+02 |
| 2.69897 | 3100.00 | 1.053458E+02 | 1.557063E+02 |
| 2.69897 | 3200.00 | 1.206547E+02 | 1.589258E+02 |
| 2.69897 | 3300.00 | 1.381862E+02 | 1.621105E+02 |
| 2.69897 | 3400.00 | 1.582697E+02 | 1.655621E+02 |
| 2.69897 | 3500.00 | 1.812634E+02 | 1.688835E+02 |
| 2.69897 | 3600.00 | 2.076115E+02 | 1.724755E+02 |
| 2.69897 | 3700.00 | 2.377915E+02 | 1.759397E+02 |
| 2.69897 | 3800.00 | 2.723359E+02 | 1.796776E+02 |
| 2.69897 | 3900.00 | 3.114119E+02 | 1.833906E+02 |
| 2.69897 | 4000.00 | 3.557235E+02 | 1.871802E+02 |
| 2.69897 | 4100.00 | 4.059523E+02 | 1.910463E+02 |
| 2.69897 | 4200.00 | 4.478723E+02 | 1.944387E+02 |
| 2.69897 | 4300.00 | 4.756654E+02 | 1.975117E+02 |
| 2.69897 | 4400.00 | 5.052222E+02 | 2.006334E+02 |
| 2.69897 | 4500.00 | 5.368947E+02 | 2.038044E+02 |
| 2.69897 | 4600.00 | 5.699158E+02 | 2.070256E+02 |
| 2.69897 | 4700.00 | 6.053054E+02 | 2.102975E+02 |
| 2.69897 | 4800.00 | 6.426926E+02 | 2.136212E+02 |
| 2.69897 | 4900.00 | 6.811091E+02 | 2.169971E+02 |
| 2.69897 | 5000.00 | 7.204271E+02 | 2.204246E+02 |
| 2.69897 | 5100.00 | 7.599681E+02 | 2.239004E+02 |
| 2.69897 | 5200.00 | 7.999548E+02 | 2.274242E+02 |
| 2.69897 | 5300.00 | 8.404049E+02 | 2.310349E+02 |
| 2.69897 | 5400.00 | 8.814434E+02 | 2.346941E+02 |
| 2.69897 | 5500.00 | 9.232759E+02 | 2.383908E+02 |
| 2.69897 | 5600.00 | 9.656605E+02 | 2.421562E+02 |
| 2.69897 | 5700.00 | 9.422075E+02 | 2.458545E+02 |
| 2.69897 | 5800.00 | 9.752131E+02 | 2.494166E+02 |
| 2.69897 | 5900.00 | 1.009375E+03 | 2.530195E+02 |
| 2.69897 | 6000.00 | 1.044773E+03 | 2.566733E+02 |
| 2.69897 | 6100.00 | 1.081381E+03 | 2.603905E+02 |
| 2.69897 | 6200.00 | 1.118468E+03 | 2.640712E+02 |
| 2.69897 | 6300.00 | 1.156131E+03 | 2.674953E+02 |
| 2.69897 | 6400.00 | 1.194912E+03 | 2.713499E+02 |
| 2.69897 | 6500.00 | 1.235878E+03 | 2.749029E+02 |
| 2.69897 | 6600.00 | 1.276649E+03 | 2.783785E+02 |
| 2.69897 | 6700.00 | 1.322901E+03 | 2.819999E+02 |
| 2.69897 | 6800.00 | 1.369 [illegible] 03 | 2.854493E+02 |
| 2.69897 | 6900.00 | 1.415[illegible]E+03 | 2.890933E+02 |
| 2.69897 | 7000.00 | 1.465016E+03 | 2.927437E+02 |
| 2.69897 | 7100.00 | 1.517612E+03 | 2.962544E+02 |
| 2.69897 | 7200.00 | 1.574875E+03 | 2.993096E+02 |
| 2.69897 | 7300.00 | 1.638452E+03 | 3.023960E+02 |
| 2.69897 | 7400.00 | 1.705319E+03 | 3.037842E+02 |
| 2.69897 | 7500.00 | 1.805863E+03 | 2.879385E+02 |
| 2.69897 | 7600.00 | 1.912336E+03 | 2.729954E+02 |
| 2.69897 | 7700.00 | 2.026087E+03 | 2.587922E+02 |
| 2.69897 | 7800.00 | 2.144486E+03 | 2.452777E+02 |
| 2.69897 | 7900.00 | 2.270925E+03 | 2.325638E+02 |
| 2.69897 | 8000.00 | 2.404816E+03 | 2.204439E+02 |
| 2.69897 | 8100.00 | 2.546606E+03 | 2.089035E+02 |



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| | | | |
|---|---|---|---|
| 2.09897 | 8200.00 | 2.096754E+03 | 1.981200E+02 |
| 2.09897 | 8300.00 | 2.055754E+03 | 1.878121E+02 |
| 2.09897 | 8400.00 | 3.024129E+03 | 1.780406E+02 |
| 2.09897 | 8500.00 | 3.292436E+03 | 1.687775E+02 |
| 2.09897 | 8600.00 | 3.391347E+03 | 1.599963E+02 |
| 2.09897 | 8700.00 | 3.005291E+03 | 8.944559E+00 |
| 2.09897 | 8800.00 | 4.010499E+03 | -2.342372E+00 |
| 2.09897 | 8900.00 | 4.304406E+03 | -4.807999E+01 |
| 2.09897 | 9000.00 | 4.772941E+03 | -3.358206E+02 |

THE DATA FOR SUBROUTINE REDCP3:

GEOMETRY(HEATED INTERNAL SURFACE ELEMENT #1)

| I | VOL | MAT | #CON | 12 | A | 13 | A | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 1 | 1 | 2 | 1.789E+01 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 2 | 1.547E-04 | 1 | 1 | 3 | 9.692E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 3 | 1.771E-04 | 1 | 1 | 4 | 1.089E+01 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 4 | 1.944E-04 | 1 | 1 | 5 | 1.169E+01 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 5 | 2.116E-04 | 1 | 1 | 6 | 1.269E+01 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 6 | 2.292E-04 | 1 | 1 | 7 | 1.369E+01 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 7 | 2.465E-04 | 1 | 1 | 8 | 9.958E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 8 | 5.451E-04 | 1 | 1 | 9 | 8.349E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 9 | 6.146E-04 | 1 | 1 | 10 | 9.341E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 10 | 6.840E-04 | 1 | 1 | 11 | 1.034E+01 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 11 | 7.535E-04 | 1 | 1 | 12 | 1.134E+01 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 12 | 8.229E-04 | 1 | 1 | 13 | 1.234E+01 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 13 | 8.924E-04 | 1 | 1 | 14 | 1.334E+01 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 14 | 9.618E-04 | 1 | 1 | 15 | 1.434E+01 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 15 | 1.031E-03 | 1 | 1 | 16 | 1.534E+01 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 16 | 1.101E-03 | 1 | 1 | 17 | 1.634E+01 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 17 | 1.170E-03 | 1 | 1 | 18 | 1.177E+01 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| 18 | 1.240E-03 | 1 | 1 | 0 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 |

THE DATA FOR SUBROUTINE ABAR03 # 1

SURFACE AREA AND RADIUS DATA FOR ABAR03 #1

| SURFACE ELEMENT | AREA(FT**2) | RADIUS(FT) |
|---|---|---|
| 1 | .03625 | .03625 |

DATA FOR ABAR03 BLOCK 1 WITH TIME = 2.0000E-01 SECONDS.

| REC ENTH | REC Q CH | P LOCAL | CM/CH | LEWIS # | BLOWING PARAM | SPACE TEMP R |
|---|---|---|---|---|---|---|
| 1.287008+03 | 3.694675+02 | 1.000015+02 | 1.000008+00 | 1.000008+00 | 4.000308-01 | 1.000008-04 |

| NODE | Q CONV | Q CONV TOT | Q RAD IN | IN RAD TOT | M DOT | MASS LOST | ACCUM Q ERR |
|---|---|---|---|---|---|---|---|
| T SURF | Q CHEM | Q CHEM TOT | Q RAD OUT | OUT RAD TOT | REC RATE | RECESSION | Q REF |
| BETA | Q COND | Q COND TOT | Q SENS | Q SENS TOT | CHR/CH | H WALL | CM |
| 1 | 2.71150E+03 | 0.00000E+00 | 0.00000E+00 | 0.00000E+00 | 6.929115-01 | 0.00000E+00 | 0.00000E+00 |
| 4.44223E+03 | 8.24777E+02 | 0.00000E+00 | 0.00000E+00 | 0.00000E+00 | 7.649093E-02 | 0.00000E+00 | -5.69962E+02 |
| 1.74992E-01 | -3.54625E+03 | 3.04030E+00 | 5.64985E+02 | 0.00000E+00 | 1.00000E+00 | 6.03200E+02 | 3.95967E+00 |

TIME (SEC):
2.00300E-01

THERMAL CAPACITOR TEMPERATURES - DEGREES FARENHEIT

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 = | 4202.5 | 2 = | 2565.2 | 3 = | 816.3 | 4 = | 501.3 | 5 = | 335.3 | 6 = | 239.3 | 7 = | 180.3 | 8 = | 127.3 |
| 9 = | 97.3 | 10 = | 86.3 | 11 = | 82.3 | | | | | | | | | | |

CRITICAL INDEX NO. = 6, TIME STEP = 1.030076E-02 (SEC).

DATA FOR ABAR03 BLOCK 1 WITH TIME = 2.208BE-01 SECONDS.

| REC ENTH | RHO U CH | P LOCAL | CM/CH | LEWIS # | BLOWING PARAM | SPACE TEMP R |
|---|---|---|---|---|---|---|
| 1.28700E+03 | 3.95967E+00 | 1.00001E+02 | 1.00000E+00 | 1.00300E+00 | 4.00000E-01 | 1.00000E-04 |

| NODE | Q CONV | Q CONV TOT | Q RAD IN | IN RAD TOT | M DOT | MASS LOST | ACCUM Q ERR |
|---|---|---|---|---|---|---|---|
| T SURF | Q CHEM | Q CHEM TOT | Q RAD OUT | OUT RAD TOT | REC RATE | RECESSION | Q NET |
| BETA | Q COND | Q COND TOT | Q SENS | Q SENS TOT | CHB/CH | H WALL | CM |
| 1 | 2.91155E+03 | 5.85616E+01 | 0.00000E+00 | 0.00000E+00 | 6.48599E-01 | 1.39673E-02 | -2.08346E-03 |
| 4.39365E+03 | 7.41412E+02 | 1.63341E+01 | 0.00000E+00 | 0.00000E+00 | 7.01187E-02 | 1.50998E-03 | -2.20972E+00 |
| 1.74961E-01 | -3.20365E+03 | -6.97994E+01 | 4.51521E+02 | 4.74581E+00 | 9.36217E-01 | 5.01604E+02 | 3.70711E+00 |

TIME (SEC):
2.20882E-01

THERMAL CAPACITOR TEMPERATURES - DEGREES FARENHEIT

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 = | 3934.0 | 2 = | 2541.9 | 3 = | 1041.9 | 4 = | 572.0 | 5 = | 369.3 | 6 = | 264.1 | 7 = | 198.7 | 8 = | 137.7 |
| 9 = | 102.6 | 10 = | 88.4 | 11 = | 83.0 | 12 = | 80.9 | 13 = | 80.4 | | | | | | |

CRITICAL INDEX NO. = 6, TIME STEP = 1.087841E-02 (SEC).

DATA FOR ABAR03 BLOCK 1 WITH TIME = 2.317[illegible]E-01 SECONDS.

| REC ENTH | RHO U CH | P LOCAL | CM/CH | LEWIS # | BLOWING PARAM | SPACE TEMP R |
|---|---|---|---|---|---|---|
| 1.28700E+03 | 3.95967E+00 | 1.00001E+02 | 1.00000E+00 | 1.00000E+00 | 4.00000E-01 | 1.00000E-04 |

| NODE | Q CONV | Q CONV TOT | Q RAD IN | IN RAD TOT | M DOT | MASS LOST | ACCUM Q ERR |
|---|---|---|---|---|---|---|---|
| T SURF | Q CHEM | Q CHEM TOT | Q RAD OUT | OUT RAD TOT | REC RATE | RECESSION | Q NET |
| BETA | Q COND | Q COND TOT | Q SENS | Q SENS TOT | CHB/CH | H WALL | CM |
| 1 | 2.92529E+03 | 9.02337E+01 | 0.00000E+00 | 0.00000E+00 | 6.48389E-01 | 2.10239E-02 | -1.63727E-03 |
| 4.38177E+03 | 7.39757E+02 | 2.43995E+01 | 0.00000E+00 | 0.00000E+00 | 7.00951E-02 | 2.27276E-03 | 1.41602E-01 |
| 1.74959E-01 | -3.21674E+03 | -1.04650E+02 | 4.46166E+02 | 4.91183E+00 | 9.35908E-01 | 4.97637E+02 | 3.70569E+00 |

TIME (SEC):
2.31761E-01

THERMAL CAPACITOR TEMPERATURES - DEGREES FARENHEIT

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 = | 3922.1 | 2 = | 2546.3 | 3 = | 1111.4 | 4 = | 617.2 | 5 = | 393.1 | 6 = | 275.8 | 7 = | 208.1 | 8 = | 142.5 |
| 9 = | 105.6 | 10 = | 89.7 | 11 = | 83.5 | 12 = | 81.1 | 13 = | 80.4 | 14 = | 80.3 | | | | |

CRITICAL INDEX NO. = 6, TIME STEP = 1.119474E-02 (SEC).

DATA FOR ABAR03 BLOCK 1 WITH TIME = 2.5453E-01 SECONDS.

| REC ENTH | RHO U CH | P LOCAL | CM/CH | LEWIS # | BLOWING PARAM | SPACE TEMP R |
|---|---|---|---|---|---|---|
| 1.28700E+03 | 3.95967E+00 | 1.00001E+02 | 1.00000E+00 | 1.00000E+00 | 4.00000E-01 | 1.00000E-04 |

| NODE | Q CONV | Q CONV TOT | Q RAD IN | IN RAD TOT | M DOT | MASS LOST | ACCUM Q ERR |
|---|---|---|---|---|---|---|---|



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# NOMENCLATURE

| | |
|---|---|
| $A$ | area |
| $ALPHA_w$ | absorptivity of the surface evaluated at $T_w$ |
| $C_H$ | heat transfer Stanton number ($q_{conv}/\rho_e U_e \Delta H$) |
| $C_m$ | mass transfer Stanton number ($m_d/\rho_e U_e \Delta Z$) |
| $c_p$ | specific heat |
| $e$ | natural logarithm base |
| $F$ | radiation view factor |
| $h_{a,w}$, $h_{a,2}$ | the sensible enthalpies above $T_{ref}$ of an ablative material evaluated at $T_w$ and $T_2$, respectively |
| $h_r$ | sensible recovery enthalpy |
| $h_w$ | sensible gas enthalpy at the wall |
| $\Delta H_{i,w}$ | chemical enthalpy change of each diffusing specie i due to reactions with the ablative material. $\Delta H_{i,w}$ is evaluated at $T_w$, and equals $H_{i,w} - \overline{H}_{rg,w}$ |
| $H$ | total enthalpy above $T_{ref}$ (i.e., H = sensible + chemical enthalpies) |
| $H_{a,w}$ | total enthalpy above $T_{ref}$ of solid ablative materials evaluated at $T_w$ |
| $\overline{H}_{dg,w}$ | average total enthalpy above $T_{ref}$ of gases diffusing to the surface, evaluated at $T_w$ |
| $\overline{H}_{e,w}$ | average total enthalpy above $T_{ref}$ of gases at the thermal temperature boundary layer edge, evaluated at $T_w$ |
| $H_r$ | total recovery enthalpy above $T_{ref}$ |

| | |
|---|---|
| $H_{i,w}$ | total enthalpy above $T_{ref}$ of gaseous specie i diffusing to the surface, evaluated at $T_w$ |
| $H_{rg,w}$ | average total enthalpy (above $T_{ref}$) of the reacted gases at the surface, evaluated at $T_w$ |
| $K_{i-j}$ | thermal conductivity between elements i and j |
| $L_{i-j}$ | distance from element i to element j |
| $m_a$ | ablative mass loss rate per unit area |
| $m_d$ | mass flow rate per unit area of all gases diffusing to the surface |
| $m_i$ | mass flow rate per unit area of gaseous species i diffusing to the surface |
| $m_{mech}$ | mechanical erosion mass loss |
| $m_{rg}$ | mass flow rate per unit area of all reacted gases leaving the surface via diffusion and mass transfer |
| N | number of species diffusing to the wall |
| $P_L$ | local pressure |
| $q_a$ | chemical heating rate per unit area due to ablative material reacting at the surface |
| $q_{chem}$ | chemical heating rate per unit area ($q_{chem} = q_d + q_a$) |
| $q_{cond}$ | conduction heat transfer rate per unit area |
| $q_{conv}$ | convection heating rate per unit area |
| $q_d$ | chemical heating rate per unit area due to diffusing gases reacting at the surface |
| $q_{in}$ | total heating rate per unit area due to laser heating and/or other radiative heating |

| | |
|---|---|
| $q_{las}$ | incident laser heating rate per unit area |
| $q_{rad\ in}$ | heating rate per unit area due to radiation to the surface |
| $q_{rad\ out}$ | heat loss rate per unit area due to radiation from the surface |
| $q_{sens}$ | heating rate per unit area required to raise the sensible energy of the solid ablative material from $T_2$ to $T_w$ |
| $Q_{vap}$ | heat of vaporization (Btu/lb) |
| $T_{ref}$ | reference temperature at which chemical and sensible enthalpies are zero ($T_{ref}$ is often set at 536°R) |
| $T_{sp}$ | space temperature, to which the surface radiates |
| $T_w$, $T_2$, $T_3$ | temperature at the wall and at interior nodes 2 and 3 |
| $U_e$ | velocity parallel to the surface at the boundary layer edge |
| V | element volume |
| VIEW | view factor for the incident laser beam |
| $Z_{i,e}$, $Z_{i,w}$ | diffusion mass transfer potentials of specie i evaluated at the boundary layer edge and at the wall respectively (these potentials are discussed in Ref. 5) |
| $\alpha$ | blowing coefficient, $\frac{2\lambda m_a}{\rho_e U_e C_H}$ |
| $\beta$ | ablation to diffusion mass loss ratio defined as $\beta = \frac{m_a}{\rho_e U_e (C_m)_b}$ |
| $\epsilon_w$ | thermal emissivity of the surface evaluated at $T_w$ |

| | |
|---|---|
| $\lambda$ | an empirical constant known as the "blowing parameter" (usually $\lambda = 0.5$ for laminar flow and $\lambda = 0.4$ for turbulent flow) |
| $\rho$ | material density |
| $\rho_e$ | density at the boundary layer edge |
| $\sigma$ | Stefan-Boltzman constant |
| $\tau_a$, $\tau_b$, $\tau_c$ | times at three consecutive time steps (a, b, and c) |

Subscripts

| | |
|---|---|
| a | ablative material |
| b | corrected for blowing |
| d | diffusion |
| dg | diffusion gas |
| e | boundary layer edge |
| i | specie i diffusing to the wall |
| rg | radiating gas |
| r | recovery condition |
| w | wall |
| 2-5 | from node 2 to node 5 |

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